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Demonstration of Wellman-Lord/Allied Chemical FGD Technology: Boiler Operating Characteristics

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Boiler Operating Characteristics

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16. ABSTRACT

The report gives results of an intensive examination and characterization of a coal-fired boiler prior to retrofit of a full scale flue gas desulfurization (FGD) unit employing the Wellman-Lord/Allied process. The test established a baseline profile of the boiler for later comparison both with design and operating conditions of other boilers for which the Wellman-Lord/Allied process is potentially applicable, and with operating performance after retrofit of the FGD unit. It also established a baseline profile during operation of the boiler at conditions other than normal which have the potential for affecting the performance of the Wellman-Lord/Allied FGD unit. Boiler operating performance was examined for its economic performance, overall energy balance, and the performance of auxiliaries. Detailed profiles of the flue gas at the proposed boiler/FGD unit interface were determined at varying boiler control settings including operation at below normal sulfur, higher than normal flue gas volumes, and higher than normal grain loadings. The tests were performed on Boiler No. 11 of Northern Indiana Public Service Company's Mitchell Power Station.

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DEMONSTRATION OF WELLMAN-LORD/ALLIED CHEMICAL FGD TECHNOLOGY: BOILER OPERATING CHARACTERISTICS

by

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EXECUTIVE SUMMARY

The Environmental Protection Agency (EPA) is actively engaged in an extensive program of technology development in the area of flue gas desulfurization (FGD). A major element of this program is the demonstration of candidate FGD processes which are nearing commercial applicability. These demonstration projects comprise operation of an FGD unit of such size and for such duration as to permit valid determinations of the technical and economic practicality of the process for potential industrial users. Among the candidate processes selected for demonstration is the Wellman-Lord/Allied Process, a regenerable process based on the removal of sulfur dioxide from flue gases by a sodium sulfite scrubbing solution and on the subsequent recovery and reduction of the sulfur dioxide to elemental sulfur. The Wellman-Lord/Allied demonstration unit has been installed at Northern Indiana Public Service Company's (NIPSCO) D.H. Mitchell Power Station and is designed to treat the total flue gas from NIPSCO's 115MW coal-fired Boiler No. 11. This report presents the results of the Baseline Test, an intensive examination and characterization of Boiler No. 11 conducted prior to installation of the Wellman-Lord/Allied FGD Unit.

TEST OBJECTIVES AND SCOPE

Demonstration goals include an evaluation showing that the Wellman-Lord/Allied Process has widespread applicability among the total population of utility boilers. Effects, if any, on boiler operation from retrofit of the FGD unit must also be determined. Based on these goals, the major objectives of the Baseline Test were:

1. A detailed profile of Boiler No. 11 as a baseline for comparison with other boiler design and operating conditions.

2. A detailed profile of Boiler No. 11 as a baseline for comparing operating performance before and after retrofit of the FGD unit.
3. Baseline operation of Boiler No. 11 at operating conditions other than normal which have the potential for affecting the performance of the FGD demonstration unit.

The test program initiated for the attainment of these objectives focused on the following three major test categories:

1. Boiler operating performance was examined with emphasis on its economic performance and on its overall energy balance. Included also were evaluations of the performance of the major auxiliaries such as coal pulverizers, air preheaters, and the electrostatic precipitator.
2. The properties of the flue gas at the proposed boiler/FGD unit interface were characterized at both normal and off-normal operating conditions of the boiler. Off-normal operation included operation with a low sulfur coal, with higher than normal combustion air, with higher than normal air inleakage to the flue gas simulated, and with higher than normal flue gas grain loadings.
3. Relationships were established between boiler control settings and the dependent flue gas properties.

BASELINE BOILER PERFORMANCE

Economic Performance

Steam side pressures and temperatures were in fairly good agreement with design values, indicating that the boiler was being operated close to the design control settings. The fuel burned was essentially the same as the design fuel employed for the boiler acceptance tests. Despite this, boiler efficiency calculated by the heat loss method was 1% to 3% less than the manufacturer's efficiency rating. Heat rates were thus correspondingly higher than the design heat rates. Below 92MW, differences between actual and design efficiencies increased with a decrease in load. The major loss affecting efficiency and heat rate was the heat exhausted to the stack due to higher than design dry flue gas volumes.

The overall energy balance of the boiler, in percent of input energy, was as follows:

Boiler Losses	15.1-20.7
Auxiliaries Energy Consumption	1.9- 2.5
Net Output	28.3-32.2

Turbine and generator losses and heat rejection to the turbine condenser make up the remainder of the energy balance. The net output is that percentage of total input energy as electrical energy available for distribution. During baseline testing, net output was below design as a result of higher than design boiler losses. Auxiliary energy consumption was not excessive compared to design.

Energy available from the steam averaged 3.9% higher than the average design energy requirements. The Wellman-Lord/Allied FGD Unit will consume about 8% of the boiler main steam output, thus derating the boiler.

Performance of Auxiliaries

Particle size of the pulverized coal was within design specifications. However, maintenance requirements on the coal mills were rather severe during the test period. Operation with one or more mills out of service was required during several tests. Capacity of the mills seemed to be sufficient to handle loads up to 92MW (80% of full load) during periods of limited equipment availability.

The air heaters were washed just prior to the start of the field test work. Heat recovery was from 9.9% to 17.2% of the total heat input to the boiler, with recoveries substantially higher at minimum load. The higher excess air requirements at a low load factor seems to improve the heat recovery performance.

Particulate collection efficiencies of the electrostatic precipitator at 92MW and 115MW (full load) were substantially below a design efficiency of 98.5%. At 46MW, design collection efficiencies were achieved.

BASELINE FLUE GAS CHARACTERIZATION

Tests were conducted to obtain a physical-chemical profile of the flue gas at normal operating conditions and at selected off-normal operating conditions. Much of the data collected was for documentation of baseline conditions for later comparison during operation with the retrofitted FGD unit. Measurements were also made to compare the flue gas parameters with the corresponding design parameters of the Wellman-Lord/Allied Unit, the boiler, and with a typical regulatory performance standard.

Potential Effect on FGD Unit

Flue gas properties having the potential to affect the performance of the FGD unit were determined. The test results are summarized as follows:

- Higher than design flue gas rates were found to have a dilution effect on SO_2 concentration which might adversely affect absorber efficiency.

- SO_2 concentrations at 92MW were higher than design despite dilution effects. This should not affect absorber performance but there would be an increased demand on the SO_2 recovery and reduction units.
- Rates and concentrations of oxygen and SO_3 were higher than design. Sulfate purge rates are a function of oxidation rates due to the oxygen levels in the flue gas and a function of the SO_3 levels in the flue gas.
- Particulate emission rates and grain loadings were significantly higher than specified for the Wellman-Lord/Allied design, primarily as a result of low dust collector efficiencies. Higher than design grain loadings at the inlet of the absorber might be expected at these conditions. Additionally, higher grain loadings will result in an increase in the fly ash purge rates.
- Fluoride and chloride were found in the flue gas. Concentration of the chloride by recirculation of the fly ash collection stream or in the absorber recirculating stream could present corrosion problems.

Effect of Off-Normal Operation

Special tests were conducted at selected off-normal operating conditions. The tests will be repeated after retrofit of the FGD unit to observe these effects:

- High grain loading - to simulate effect of grain loading on Demonstration Unit performance.
- Excess of air inleakage - to maximize flue gas volume.

- Low sulfur coal - to examine effect of a low concentration of SO_2 in the flue gas.

The effects of high grain loadings, flue gas volumes, and low SO_2 concentrations were observed. An attempt to maximize NOx formation by increasing the combustion air was not successful.

DEPENDENCY ON BOILER CONTROL SETTINGS

During testing at normal operation, the only independent variables which were varied which might change the flue gas profile were load and soot blowing. Major effects on flue gas volume and concentration of the flue gas components occurred from variations in the excess air, which is load dependent. Thus, emission rates of SO_2, NOx, and fly ash increased with load whereas concentrations of these components were dependent on the amount of excess air, assuming a linear variation in flue gas volume with load. Concentrations of SO_2 and particulate matter and the ratio of SO_2 to O_2 increased with load due to lower volume as a result of decreasing amounts of excess air with increasing load. Particle emissions showed more dependence on load than would have occurred with the electrostatic precipitator performing at design efficiency. Flue gas volume at actual temperature and pressure was also dependent on load due to an increase in temperature with load.

Particulate rates at the inlet to the air heaters (upstream of the electrostatic precipitator) were noticeably higher during soot blowing. These comparisons were made at 92MW. However, no effect from soot blowing was apparent on the downstream side of the electrostatic precipitator.

Composition of the coal is another boiler control setting affecting the flue gas profile. However, there were no noticeable effects on the flue gas on a dry basis from variations in coal composition. Moisture in the coal varied more than any other component of the coal and this would have a volume effect. However, since the volume effect due to excess air was much greater, the effect of coal moisture was not the controlling variable affecting flue gas volume.

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METRIC EQUIVALENTS

To Convert From:	To:	Multiply By:
Tons SOx/year	Kilograms SOx/year	907
Pounds/square inch (psi)	Kilograms/square centimeter (Kg/cm^2)	.0703
Cubic feet/minute (cfm)	Cubic meter/minute (m^3/min)	.0283
SO_2 parts per million (ppm by weight)*	Micrograms/cubic meter (µg/m^3 by weight)	2620
Inches mercury (in. Hg)	Millimeters mercury (mm Hg)	25.4005
Inches water (in. H_2O at 60°F)	Millimeters mercury (mm Hg at 15.6 °C)	1.8663
Grains/standard cubic foot (gr/scf)	Grams/normal cubic meter (gm/Nm^3)	2.288
Pounds/hour (lbs/hr.)	Kilograms/hour (Kg/hr.)	0.4536
BTU/pounds (BTU/lbs.)	Calories/gram (Cal./gm.)	0.556
BTU/hour (BTU/hr.)	Kilogram-Calories/hour (Kg-Cal/hr.)	0.252

*SO_2 normally reported as ppm by volume.

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The authors wish to express appreciation to Messrs. Mann, McGrath, Matteizzi, and Thalman of Northern Indiana Public Service Company and members of their staff for their assistance in the collection of the field test data and their cooperation in operating Unit No. 11 of the D.H. Mitchell Station at the desired operating conditions for testing.

1.0 INTRODUCTION

1.1 BACKGROUND

The Environmental Protection Agency (EPA) is actively engaged in a number of programs to demonstrate sulfur oxide emission control processes applicable to stationary sources. These demonstration programs comprise operation of an emission control unit of such size and for such duration as to permit valid technical and economic scaling of operating factors to define the commercial practicality of the process for potential industrial users. Among the candidate processes being evaluated, having the potential to become a major SOx emission control method, is the Wellman-Lord/Allied (WL/Allied) process developed by Davy Powergas (formerly Wellman-Power Gas) and Allied Chemical. The demonstration unit is being constructed by Davy Powergas and operated by Allied Chemical under contract to the Northern Indiana Public Service Company (NIPSCO) and to the Environmental Protection Agency (EPA). The WL/Allied process as developed by the two design organizations is based upon the recovery of sulfur dioxide (SO_2) in concentrated form and its subsequent reduction to elemental sulfur. The product is to be sold to partially offset the process costs. This is the first coal-fired Wellman-Lord application, also the first joint Wellman-Lord/Allied installation.

Environmental Engineering Division of TRW Inc., under contract to the Industrial Environmental Research Laboratory - RTP of the EPA, will provide the test services required for an in-depth evaluation of the demonstration unit. The tests will be performed on the NIPSCO boiler No. 11 and on a retrofitted demonstration unit, located at D.H. Mitchell Power Station, Gary, Indiana. Unit No. 11 is hereafter referred to as Mitchell No. 11. The Test and Evaluation (T&E) program consists of three major test phases:

- The Baseline Test
- The Acceptance Test
- The Demonstration Test and Evaluation

This report describes the results of the Baseline Test.

Preceding tasks of the T&E Program include:

Job No. 1: Preparation of Work Plan Manual (completed)

Job No. 2: Preparation of User Survey/Test Criteria report (completed)

Job No. 3: Preparation of Baseline Test Plan (completed)

Job No. 4: The Baseline Test. The Baseline Test was conducted according to the procedures specified in the Baseline Test Plan

Job No. 5: Preparation of Acceptance Test Plan (completed)

Job No. 6: Preparation of Demonstration Test Plan (completed)

1.2 REPORT SYNOPSIS

The Baseline Test was performed in order to fully characterize the outlet flue gas of the boiler and to obtain boiler material and energy balances. The Baseline Test was the first leg of the T&V program, to be followed by the Acceptance Test and the Demonstration Test and Evaluation. The Plan of the two latter test programs are reported under separate covers(I)(II).

Details of the Baseline Test objectives are discussed in Section 2.0, along with a summary of the test data. The following parameters were the major ones treated as independent variables in order to determine their effect on the outlet flue gas:

1. Boiler load
2. Soot blowing status
3. Coal composition (especially % sulfur in coal)
4. Inleakage and excess air
5. ESP field strength

Sets of tests were typically performed in replicates of three in order to thoroughly develop the effect of each parametric variation separately. Parameters 1, 2 and 3 represent parameters which are ordinarily varied during normal operations, the extent of their planned alteration during the Baseline Test was thus determined by examining actual plant operation. Parameters 4 and 5, which are usually dependent on such independent variables as boiler load and maintenance cycle, were examined chiefly because of their effects on grain loading and percent oxygen in the flue gas.

The test data is then discussed in detail in the next section of the report (Section 3.0). The problems encountered in conducting the test are described in Section 4.0. Based on the site-dependent experience gained during the Baseline Test, recommendations are submitted for initiating improvements in the subsequent Acceptance and Demonstration test phases of the

T&E program (Section 5.0). Following a description of Mitchell No. 11 (Appendix A), complete test results are documented in Appendix B. Test methods (Appendix C) and the field test logs (Appendix D) are also appended.

Trends and correlations of the various parameters examined are indicated in graphs and tables throughout the report. Properly used, the data in this report can and has acted as a powerful tool for making T&E design and operating decisions critical to the program's success.

2.0 TEST SUMMARY

2.1 BASELINE TEST OBJECTIVES

The Work Plan Manual(1) lists the three primary objectives of the T&E program. These are:

1. Verification of the reduction in pollutants achieved by the WL/Allied process demonstration unit.
2. Validation of the estimated technical and economic performance of the demonstration unit.
3. Assessment of the applicability of the WL/Allied process to the general population of utility boilers.

Demonstration goals include an evaluation showing that the WL/Allied Process has widespread application among the total population of utility boilers (Objective No. 3 above). Effects, if any, on boiler operation from retrofit of the demonstration desulfurization unit must also be demonstrated. Based on these goals, the Baseline Test objectives were to:

1. Establish a detailed profile of Mitchell No. 11 as a baseline for comparison with other boiler design and operating conditions.
2. Establish a detailed profile of Mitchell No. 11 as a baseline for comparing operating performance before and after retrofit.
3. Where possible, under controlled test conditions, vary Mitchell No. 11 operating variables which have the potential for affecting the performance of the demonstration unit.

The technical approach taken in baseline testing of Mitchell No. 11 was as follows:

1. Define the relationship between control settings and operating conditions for Mitchell No. 11, and flue gas properties at the demo./steam generator interface.

2. Characterize existing (baseline) performance of the unit in terms of emission levels and economics (heat rate).
3. Obtain quantitative baseline data which when combined with control system demonstration data can be used to support the establishment of realistic pollution control performance standards.
4. Obtain site-dependent experience in manual testing and measurement procedures to be used in the subsequent Acceptance and one-year Demonstration phases.
5. Obtain quantitative information on the overall operability and reliability of Mitchell No. 11.

2.2 BASELINE BOILER PERFORMANCE

2.2.1 Economic Performance

Steam side pressures and temperatures were in fairly good agreement with design values, indicating that the boiler was being operated close to the design control settings. The fuel burned was essentially the same as the design fuel employed for the boiler acceptance tests. Despite this, boiler efficiency calculated by the heat loss method was 1% to 3% less than the manufacturer's efficiency rating. Heat rates were thus correspondingly higher than the design heat rates. Below 92MW, differences between actual and design efficiencies increased with a decrease in load. The major loss affecting efficiency and heat rate was the heat lost due to dry flue gas volumes in excess of design.

The overall energy balance of the boiler, in percent of input energy, was as follows:

Boiler Losses	15.1-20.7
Auxiliaries Energy Consumption	1.9- 2.5
Net Output	28.3-32.2

Heat rejection to the turbine condenser and turbine and generator losses make up the remainder of the energy balance. The net output is that percentage of total input energy as electrical energy available for distribution. During baseline testing, net output was below design as a result of higher than design boiler losses. Auxiliary energy consumption was not excessive compared to design.

Energy available from the steam averaged 3.9% higher than the average design energy requirements. The Demonstration Unit will consume 8% of the boiler steam output.

2.2.2 Performance of Auxiliaries

Particle size of the pulverized coal was within design specifications. However, maintenance requirements on the coal mills were rather severe during the test period. Operation with one or more mills out of service was required during several tests. Capacity of the mills seemed to be sufficient to handle loads up to 92MW (80%) with the limited availability of equipment.

The air heaters were washed just prior to the start of the field test work. Heat recovery was from 9.9% to 17.2% of the total heat input, with recoveries substantially higher at minimum load. The higher excess air requirements at a low load factor seems to improve the heat recovery performance.

Particulate collection efficiencies of the electrostatic precipitator at 92MW and 115MW (full load) were substantially below a design efficiency of 98.5%. At 46MW, design collection efficiencies were achieved.

2.3 BASELINE FLUE GAS CHARACTERIZATION

Tests were conducted to obtain a physical-chemical profile of the flue gas at normal operating conditions and at selected off normal operating conditions. Much of the data collected was for documentation of baseline conditions for later comparison during operation with the retrofitted Demonstration Unit. Flue gas parameters were also measured in order to compare them with corresponding design parameters of the Demonstration Unit, the boiler, and with a typical regulatory performance standard.

2.3.1 Potential Effect on Demo. Unit

Test flue gas variables having the potential to affect the performance of the desulfurization unit are summarized as follows:

- Higher than design flue gas rates were found to have a dilution effect on SO_2 concentration which might adversely affect absorber efficiency.
- SO_2 concentrations at 92MW were higher than design despite dilution effects. This should not affect absorber performance but there would be an increased demand on the SO_2 recovery and reduction units.
- Rates and concentrations of oxygen and SO_3 were higher than design. Sulfate purge rates are a function of the oxygen and the SO_3 rates.
- Particulate emission rates and grain loadings were significantly higher than called for in the Demo. Unit design, primarily as a result of low dust collector efficiencies. Higher than design grain loadings inlet the absorber might be expected at these conditions. Additionally, higher grain loadings will result in an increase in the fly ash purge rates.
- Fluoride and chloride were found in the flue gas. Concentration of the chloride by recirculation of the fly

ash collection stream or in the absorber recirculating stream could present corrosion problems.

2.3.2 Dependency on Boiler Control Settings

During testing at normal operation, the only independent variables which were varied which might change the flue gas profile were load and soot blowing. Major effects on flue gas volume and concentration of the flue gas components occurred from variations in the excess air, which is load dependent. Thus, emission rates of SO_2, NOx, and fly ash increased with load whereas concentrations of these components were dependent on the amount of excess air, assuming a linear variation in flue gas volume with load. Concentrations of SO_2 and particulate and the ratio of SO_2 to O_2 did increase with load due to lower volume as a result of decreasing amounts of excess air with increasing load. Particulate emissions showed more dependence on load than would have occurred with the electrostatic precipitator performing at design efficiency. Flue gas volume at actual temperature and pressure were also dependent on load due to an increase in temperature with load.

Particulate rates at the inlet to the air heaters were noticeably higher during soot blowing. These comparisons were made at 92MW. However, no effect from soot blowing was apparent after the electrostatic precipitator.

Composition of the coal is another boiler control setting affecting the flue gas profile. However, there were no noticeable effects on the flue gas from variations in coal composition. Moisture in the coal varied more than any other component of the coal and this would have a volume effect. However, since the volume effect due to excess air was much higher, the effect of coal moisture was not the controlling variable on volume effect.

2.3.3 Effect of Off Normal Operation

Special tests were conducted at selected off normal operating conditions. These tests will be repeated after retrofit of the Demo. Unit to observe these effects:

- High grain loading - to simulate effect of grain loading on Demo. Unit performance
- Excess of air inleakage - to maximize flue gas volume
- Low sulfur coal - to examine effect of a low concentration of SO_2 in the flue gas

The effects of high grain loadings, flue gas volumes and low SO_2 concentrations were observed. An attempt to maximize NOx formation by increasing the combustion air was not successful.

3.0 DISCUSSION OF RESULTS

3.1 EFFICIENCY AND HEAT RATES

This section describes the results obtained for evaluating the operating and economic performance of the boiler/turbine generator combination (efficiencies and heat rates) as it compares to design performance at three levels of load. The purposes of the evaluation were:

- To establish a baseline performance profile for later comparison with performance during the Demonstration.
- To define the relationship between control settings and operating conditions.
- To provide operating data for comparison with other existing boiler configurations for which the WL/Allied process has applicability.

A total of 35 tests were completed. Four series of tests were run as follows:

Test Series 1 & 3: 14 tests with boiler operating normally.

Test Series 2: 9 special tests with boiler at off normal operating conditions.

Test Series 5: 12 special tests during which boiler was burning low sulfur coal (nominal 1% sulfur content).

Test Series 4, special tests during which boiler would burn a high sulfur coal of four to five percent sulfur content, was cancelled due to inability to purchase a suitable coal. This section will focus on results obtained when the boiler was operating normally (Test Series 1 & 3). In addition, fuel quality and its effect on the performance of the coal mills will be discussed for Test Series 2.

3.1.1 Boiler Efficiency

3.1.1.1 Definitions

Boiler efficiency is determined by two methods:

1) Heat Loss Method (HLE Method) - ratio; heat input less measured heat losses to heat input:

$$\text{Eff.} = \frac{\text{heat input} - \text{heat losses}}{\text{heat input}}$$

2) Input/Output Method (I/O Method) - ratio; heat absorbed by water and steam to heat in the fuel:

$$\text{Eff.} = \frac{\text{heat available}}{\text{heat input}}$$

Of the two methods, use of the HLE method for determining efficiencies usually results in the higher values. Within the limits of measurement error, results by the two methods would be identical if all heat losses could be accounted for. The distribution of losses is discussed in 3.1.1.2 and 3.1.3.

The performance guarantees for Mitchell No. 11 were based on the HLE method using the Abbreviated Efficiency Test procedure of the ASME Power Test Code PTC 4.1(2). The same procedures were used for the tests reported herein for both the I/O and the HLE efficiency determinations.

3.1.1.2 Observed Efficiency Vs. Design Efficiency

Relevant data are shown in Table 3-1, Table B-1 and on Figure 3-1.

Measured efficiency calculated by the HLE method was less than the manufacturer's efficiency rating by about 1 to 3 percent, depending on load. The range of measured efficiency was 84.9% to 88.3% for load factors of 40% to 100% compared to design values in the range of 88.0% to 88.3%. The observed and design efficiencies are plotted on Figure 3-1 as a function of load. The HLE efficiency values for Tests 7, 22 and 23 are assumed to be outliers and are not included in the correlation. Tests 22 and 23 (Test Series 3) were performed primarily to obtain miscellaneous information about the flue gas. Due to boiler scheduling problems they were delayed nearly a full year after the other tests at normal operation. Table B-1 shows the energy from the fuel distributed to the steam and shows the various components of loss. The losses for one test at full load (118MW) are compared with the design basis losses as follows:

[illegible]

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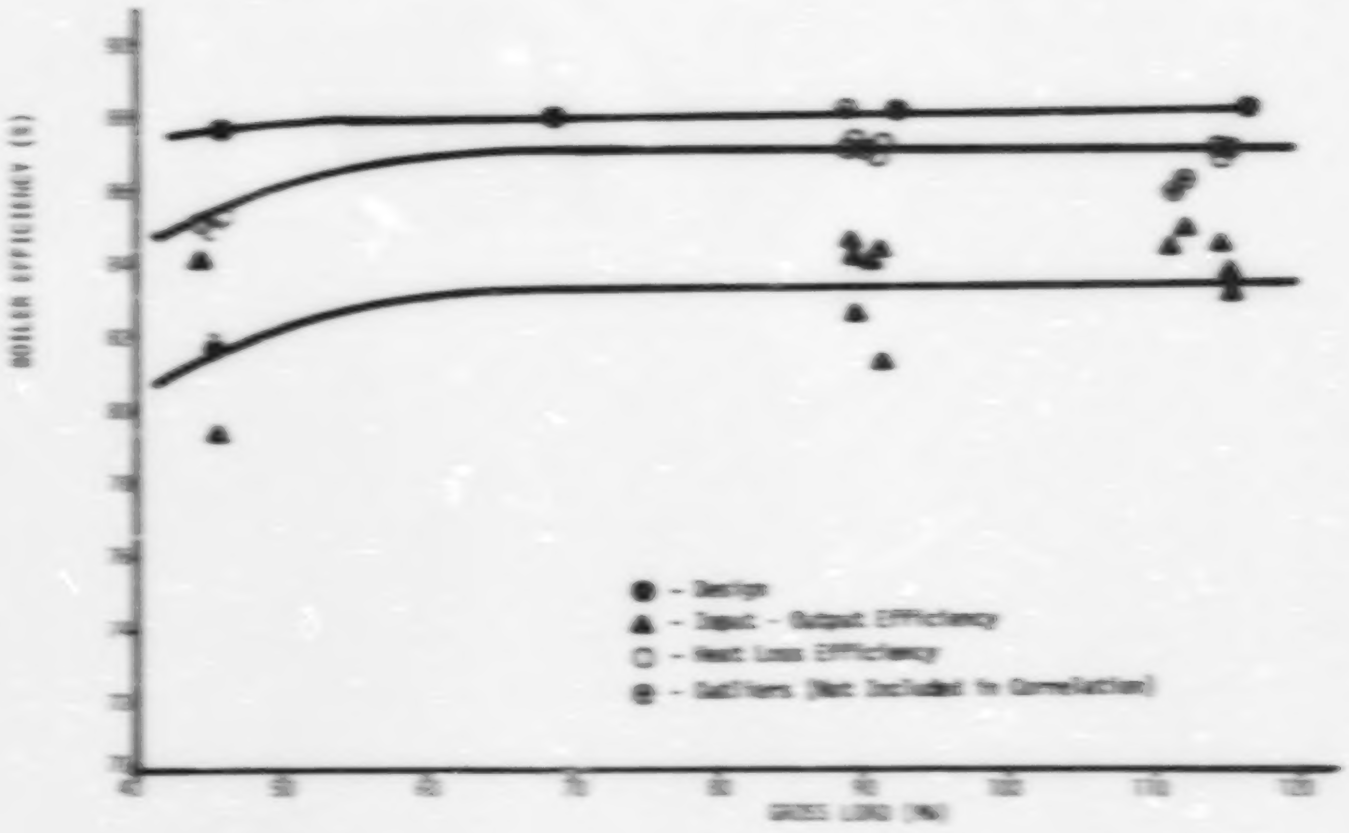
FIGURE 3-1
BOILER EFFICIENCY vs. GROSS LOAD
3% SULPHUR TESTS
TEST SERIES [illegible]



	Observed(1)(2)	Design(1)(3)
Dry Gas	6.66	4.48
Coal Moisture and Hydrogen	4.62	5.08
Moisture in Air	0.71	0.11
Carbon in Refuse	0.44	0.30
Radiation	0.50	0.23
Flue Dust Sensible Heat	0.03	----
NO in Flue Gas	0.01	----
Sub Total	12.97	10.20
Manufacturer's Margin for Unaccounted for Losses	----	1.50
Unaccounted for Losses, from I/O Method	4.02	----
Total	16.99	11.70

(1) As percent of heat input.

(2) Test No. 9, 116.1MW Gross Load.

(3) Estimated losses for design basis efficiency of 88.3% at 115MW.

The percent of total heat input unaccounted for, 4.02%, is also the margin of difference between HLE efficiency and I/O efficiency and explains the higher results obtained by the HLE method. The HLE method is usually expected to yield the more accurate results. This is due to a fourfold or greater significance of the measurement errors of the I/O method compared to the HLE method. The magnified errors in the I/O method are the result of error components on 80% or more of the heat input versus for the HLE method errors on only 20% or less of the heat input.

The unaccounted for losses which make up the margin between the efficiencies calculated by the two methods (see Figure 3-1) might consist of the following:

- Blowdown losses
- Radiation to ash pit, sensible heat in slag, latent heat of fusion of slag and unburned carbon in ash pit.
- Heat in pulverizer rejects.
- Unburned CO, hydrogen and hydrocarbons in flue gas.

3.1.2 Heat Rates

3.1.2.1 Definitions

Heat rate is the ratio of the heat input in the coal to the electrical energy output, and is expressed in units of Btu/KWH. It is the reciprocal of a corresponding efficiency term. Two heat rates are reported, gross heat rate and net heat rate, which are determined on gross and net electrical energy output respectively. The net heat rate describes the economic performance of the boiler as determined from the utilization of the total input energy.

3.1.2.2 Comparison With Design Heat Rates

Relevant data are included in Table 3-1 and on Figure 3-2.

Higher than design heat rates were observed which correspond with the lower than design efficiencies measured. Gross and net heat rates are included in Table 3-1.

3.1.3 Energy Distribution

3.1.3.1 Definitions

Relevant data are included in Table 3-2.

The performance of the boiler has been described in terms of the boiler efficiencies and the heat rates. The boiler efficiency is the efficiency for the conversion of the chemical energy of the coal/air mixture to the heat energy as represented by an increase in enthalpy of the working fluid when it

FIGURE 3-2
HEAT RATE vs. GROSS LOAD
3% SULPHUR TESTS
TEST SERIES 1&2

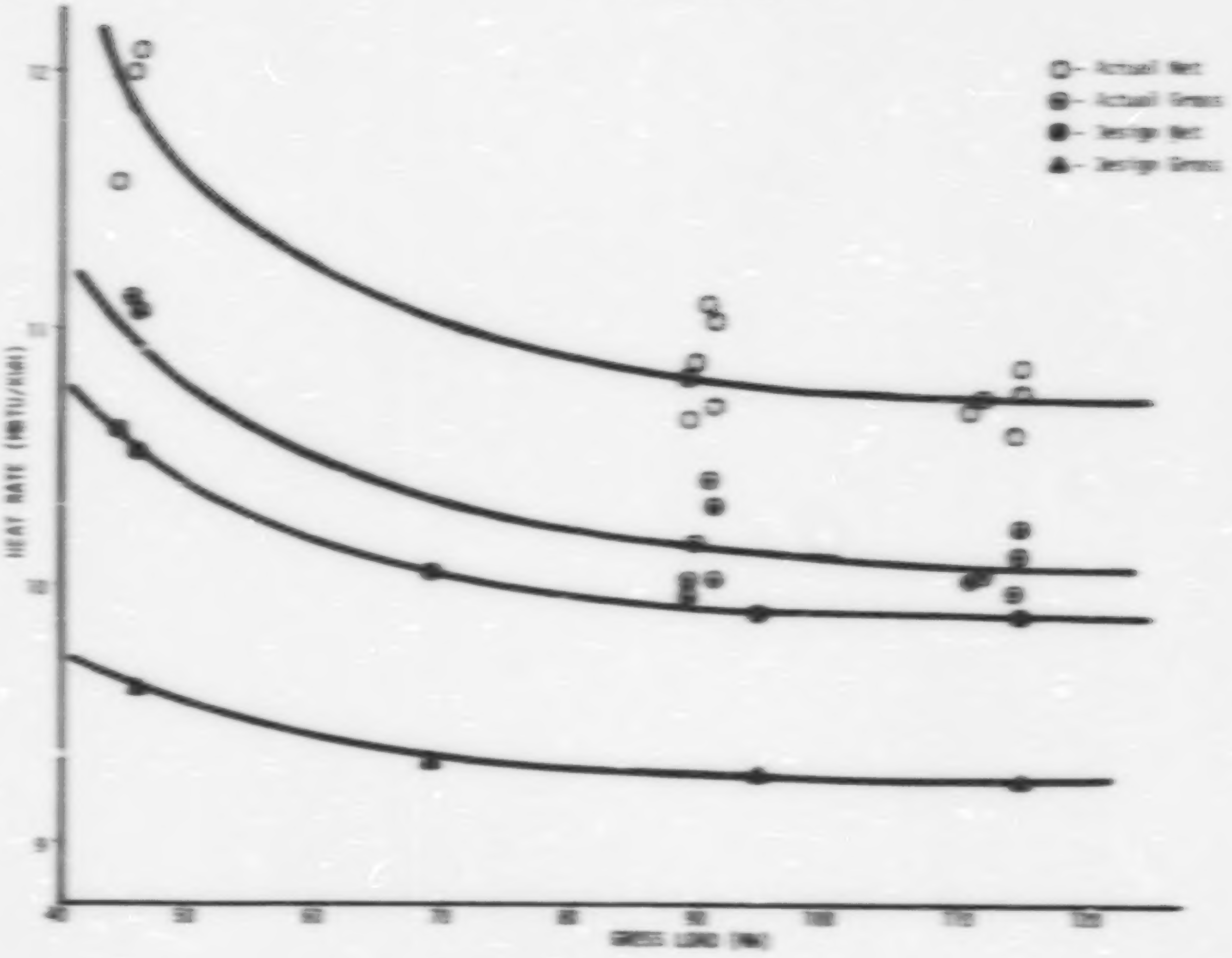


TABLE 3-2

ENERGY DISTRIBUTION DESIGN VALUES

Gross Load, MW	46	92	111.5[(1)]	115
Heat Input, MMBTU/HR[(2)]	442.5	849.8	1031.6	1064.2
Total Available Heat, MMBTU/HR	389.3	750.0	910.8	939.7
From Main Steam, MMBTU/HR	331.2	643.2	787.8	813.8
Main Steam ΔH, BTU/LB	1133.2	1066.8	1043.7	1039.6
Feedwater Flow, MLB/HR	292.3	602.9	755.4	782.8
From Reheat Steam, MMBTU/HR	58.0	106.8	123.0	125.9
Reheat Steam ΔH, BTU/LB	214.7	194.7	180.6	178.1
Reheat Steam Flow, MBTU/HR	270.2	548.3	682.5	706.9
Auxiliary Energy Consumption, MMBTU/HR	13.5	21.0	24.4	25.0
Heat Rejected Turbine & Generator Losses, MMBTU/HR	232.0	435.9	529.8	546.7
Net Power Output, MMBTU/HR	143.8	293.1	356.6	368.0
Boiler Losses, %	12.0	11.7	11.7	11.7
Auxiliary Energy, %	3.1	2.5	2.3	2.3
Heat Rejected Turbine & Generator Losses, %	52.4	51.3	51.4	51.4
Net Power Output, %	32.5	34.5	34.6	34.6

(1) Design values for this load estimated.

(2) M = Thousands

is converted from heated, pressurized water to high pressure, superheated steam. The net heat rate is a reciprocal efficiency term describing the net energy output in KWH as a fraction of the total energy input supplied by the coal. The comparison of design boiler efficiency and an efficiency corresponding to the reciprocal of the design net heat rate (overall efficiency) is as follows:

Load	Boiler Efficiency, %	Overall Efficiency, %
46MW	88.0	32.5
92MW	88.3	34.5
115MW	88.3	34.6

In other words, only about one-third of the chemical energy of the coal is converted to electrical energy. The remaining energy is distributed as follows:

- Boiler heat losses (subsection 3.1.1) - about 12%
- Heat rejected to the turbine condenser (entropy increase) - about 50%
- Energy not recovered required to drive auxiliaries - about 2.5%
- Turbine and generator losses - about 2%

The energy distribution determined from the tests are compared with the design energy distribution in the following subsection. Table 3-2 is a compilation of design values at the test load levels.

3.1.3.2 Net Energy Conversion

Relevant data are included in Table 3-3.

The weighted average net energy output (net MW-hour) was 31.3% of the input energy of the coal for the normal series of tests. Design overall efficiency varies from 32.5% to 34.6% depending on load. Energy distribution compared with design values is summarized as follows, in percent of input energy:

[illegible]

[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
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	Actual	Design
Boiler Losses	15.1 - 20.7	11.7 - 12.0
Auxiliaries Energy Consumption	1.9 - 2.5	2.3 - 3.1
Net Output	29.3 - 32.2	32.5 - 34.6

Heat rejection to the turbine condenser and turbine and generator losses make up the remainder of the energy balance.

3.1.3.3 Available Energy Of Steam

Relevant data are included in Table 3-3.

Actual heat in Btu/hr. available from the steam averaged 3.9% more than the average design values. Available energy of the steam compared with design values is summarized as follows, in MMBtu/hr.:

	Actual	Design
Main Steam(1)	346.0 - 863.0	331.2 - 813.8
Reheat Steam	50.7 - 124.6	50.0 - 125.9

(1) Includes attemperator sprays

These comparisons show that the energy available from the main steam (superheated steam) was higher than design whereas the energy available from reheat steam was lower than design.

3.1.3.4 Energy For Auxiliaries

Relevant data are included in Tables 3-1, 3-3, B-2, and B-3.

Table 3-3 shows that 1.9% to 2.7% of the available energy is used by the auxiliaries. A small amount of this energy is returned to the process. For example, a small increase in enthalpy results from flow work done by the boiler feedwater pumps.

The average current drain by each of the major pieces of auxiliary machinery has been recorded in Tables B-2 and B-3 for comparison with the equivalent data to be collected during the Demonstration.

The auxiliary power requirement is one reason for the decreasing heat rate when going from 46MW to 115MW (full load), indicated as follows:

	Auxiliary Power Consumption % of Gross Load
46MW	8.0
92MW	6.5
115MW	5.9

The relative ranking of the major auxiliaries in decreasing order of rated power requirement is as follows:

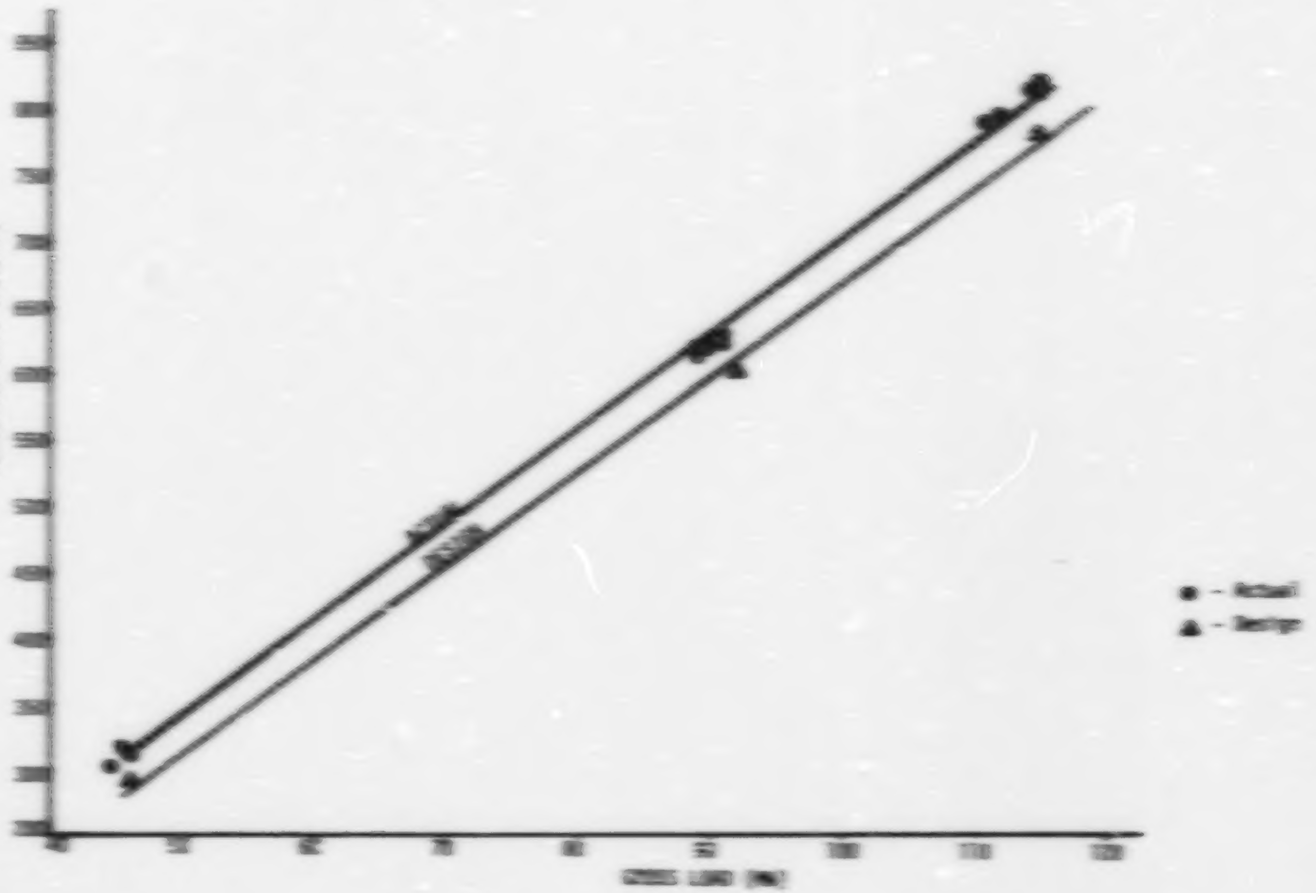
	Total HP
Boiler Feedwater Pumps (2)	3500
ID Fans (2)	1800
FD Fans (2)	1400
Circ. Water Pumps (2)	700
Coal Mills (4)	600
Condensate Pumps (2)	300

3.1.4 Feedwater Rates

Relevant data are included in Table 3-3 and on Figure 3-3.

The average feedwater flow rate was 4.1% higher than design flow rates. Steam rates were consistently higher than feedwater rates by substantial amounts, indicating a meter error. The steam rates appear to be unreasonably high. Thus, feedwater rates were used for all efficiency and energy balance determinations.

FIGURE 3-3
FEEDWATER RATE vs. GROSS LOAD
TEST SERIES [illegible]



Reheat steam is not metered and must be calculated from the feedwater rates and estimates of extraction flows.

The Demo. Unit will consume about 8% of the Mitchell No. 11 steam, thus derating the boiler. Figure 3-3 shows the design and actual feedwater rates as a function of load. Actual feedwater and steam rates during the Demonstration will be compared with these values.

3.1.6 Load Sensitive Pressure And Temperature Values

Relevant data are shown in Table B-4.

Temperatures of hot reheat steam and secondary superheater outlet steam are controlled independently of boiler load, as is pressure of secondary superheater outlet steam. All other PT levels of steam and water are sensitive to load primarily due to pressure losses in piping. Table B-4 shows the load sensitive PT levels for the series of tests during normal boiler operations. With some exceptions, the measurements were in fairly good agreement with these design values:

	Design Values		
	46MW	92MW	115MW
BFW Inlet Economizer, °F	372	434	459
No. 4 Extraction, °F	769	835	835
BFW Exit No. 3, °F	269	314	331
BFW Exit No. 4, °F	310	363	383
Cold Reheat, psig	172	363	471
Hot Reheat, psig	153	325	423
No. 4 Extraction, psig	74	163	213

3.1.6 Fuel Quality

3.1.6.1 Fuel Sources

A single source of 3% sulfur coal was not available during the Baseline tests. However, this lack of homogeneity did not result in any excessive variability in coal composition (see 3.1.6.2). Origins of the coal used were as follows:

	Mine
Tests 1-3	River King and/or Fidelity
Tests 4-5	Fidelity and/or Reclaimed
Tests 6-7	Burning Star
Tests 8-15	River King and/or Fidelity
Tests 16-19	Undetermined
Tests 20-21	River King and/or Fidelity
Tests 22-23	Reclaimed

The mines are located on the No. 6 bed located in Southwest Illinois. The coal is a high volatile bituminous, H.V.C. rank (ASTM D388 designation). Reclaimed coal is the coal taken from areas of the storage yard where a mixture of various types of coal would be expected.

Performance guarantees for Mitchell No. 11 were based on the River King coal, analysis as follows:

	As Received	Dry, Ash Free
High Heating Value, Btu/lb	11,267	14,249
Fixed Carbon, wt. %	41.64	52.66
Volatile Matter, wt. %	37.43	47.34
Oxygen, wt. %	8.72	11.03
Sulfur, wt. %	3.17	4.01
Ash (Dry Basis), wt. %	11.05	-----
Ash (Wet Basis), wt. %	9.82	-----
H_2O, wt. %	11.11	-----
Carbon, wt. %	61.65	77.97
Hydrogen, wt. %	4.43	5.60

Concentrations of components which are active in the combustion reaction are represented by the dry, ash free analysis. The dry, ash free values are useful for making comparisons between coal samples and for determining the variability of the coals.

3.1.6.2 Coal Composition

Relevant data are shown in Tables 3-4, 3-5, B-5, B-6, B-7 and B-8.

Tables 3-4 and 3-5 show the 95% confidence limits determined from the measurements for the true means of the active components for combustion: these being heating value, carbon, hydrogen and oxygen. Comparable coal parameters specified for the performance guarantees are outside these 95% confidence limits, indicating some differences between the coal used for testing and the guarantee basis coal. The heating value of the guarantee basis coal is above the higher limit of confidence. Slightly higher efficiencies might be expected from the guarantee basis coal due to lower stoichiometric air requirements as a result of higher oxygen content and a lower carbon to hydrogen ratio of the guarantee basis coal. "Raw" coal was sampled between the Mitchell No. 11 storage bunker and the coal scales. "As fired" coal is pulverized coal sampled between the coal mills and the burners.

TABLE 3-4

SUMMARY OF COAL QUALITY & VARIABILITY - AS FIRED COAL

TEST SERIES 1, 2 & 3

	Mean	Range	Mean Standard Deviation	95% Confidence Limits of the Mean
High Heating Value[(1)], MBtu/lb[(2)]	14.14	14.01-14.28	0.1	14.1-14.2
Oxygen[(1)], wt. %	9.91	9.52-10.79	0.5	9.6-10.2
Sulphur[(1)], wt. %	4.06	3.22- 4.49	0.3	4.0- 4.2
Ash, (Dry Basis), wt. %	12.40	10.40-13.84	0.9	12.0-12.8
Ash, (Wet Basis), wt. %	11.81	9.87-13.14	0.8	11.4-12.2
H_2O, wt. %	5.45	4.59- 6.31	0.6	5.1- 5.8
Carton[(1)], wt. %	78.84	76.91-79.50	0.3	78.7-79.0
Hydrogen[(1)], wt. %	5.45	5.40- 5.68	0.3	5.3- 5.6

---

(1) Dry, ash free basis

(2) M = thousands

TABLE 3-5

SUMMARY OF COAL QUALITY & VARIABILITY - RAW COAL SAMPLE

TEST SERIES 1, 2 & 3

	Mean	Range	Mean Standard Deviation	95% Confidence Limits of the Mean
High Heating Value(1), MBtu/lb(2)	14.17	14.06-14.36	0.1	14.1-14.2
Oxygen(1), wt. %	9.83	8.02-10.66	0.7	9.5-10.1
Sulphur(1), wt. %	4.08	3.37- 4.90	0.4	3.9- 4.3
Ash, (Dry Basis), wt. %	11.92	10.50-13.91	1.0	11.6-12.3
Ash, (Wet Basis), wt. %	10.69	9.30-12.65	0.9	10.3-11.1
H_2O, wt. %	10.36	8.11-11.83	1.2	9.4-10.4
Carbon(1), wt. %	79.01	77.64-81.46	0.8	78.7-79.5
Hydrogen(1), wt. %	5.41	5.15- 5.58	0.1	5.4- 5.5

(1) Dry, ash free basis

(2) M - thousands

On a dry, ash free basis the between sample variability was not excessive, see Tables 3-4 and 3-5. Heating value, carbon content and hydrogen content were particularly stable. The lack of any excess variability was welcome in view of the wide variety of coals used during the tests. No coal composition values were rejected as outliers based on standard statistical tests.

3.1.6.3 Demonstration Test Comparisons

Heat rate, efficiency, and loss calculations are based on raw coal analyses since coal rates are raw coal rates. Continuous sampling of raw coal is not feasible and therefore as fired coal samples will have to be used during the Demonstration. The major difference between raw coal and as fired coal composition is a decrease in the moisture content, but the moisture lost from the raw coal will enter the furnace entrained in the air. It is assumed that the coal rejected at the mills is minimal and thus it is assumed that the rate of as fired coal plus entrained moisture is the same as the raw coal rate. A t-test was run to determine if there are significant differences between pairs of dry basis raw coal and of as fired coal composition values. On the basis of the statistical t-test, the differences between heating values were significant at the 95% probability level but the differences between sulfur contents were not signifcant at a 95% probability level. However, the mean heating value of the raw coal was only 0.7% higher than the comparable mean for the as fired coal. It is believed, thus, that as fired coal composition adjusted for moisture can be used to determine the coal component rates without significant error. Probably the major problem will be obtaining a representative sample, considering that a large number of gross sample increments must be combined and then reduced to laboratory size. Analysis of composites created from selected groups of coal samples do not agree very well with averages of the individual samples, see Tables B-5, B-6, B-7, B-8, B-9 and B-10. Strict adherence to sample preparation procedures will be required for the continuous sampling during the Demonstration.

3.1.7 Pulverizer Performance

3.1.7.1 Operating Problems

Relevant data are shown in Figures 3-4, 3-5, 3-6 and 3-7.

Series One tests were started with only two of four mills available. Mill 2 had been forced down prior to the start of the test series due to a fire. Mill 3 was down with a broken retainer ring. One 48MW test was run with these two units out of service. Repair on Mill 2 was then completed and all of the 92MW tests and the remaining two 48MW tests were run with three mills. All four mills were available and operated for the 110MW tests of Test Series One, Two and Three.

The net effect on performance from using only two or three mills was not determined. Power consumption per unit of coal fired increases when more mills are added but the firing patterns are changed as shown in Figure 3-4 3-5, 3-6 and 3-7.

3.1.7.2 Size Reduction

Tables B-11 and B-12 present the relevant pulverizer performance data at both normal and off-normal operating conditions.

The screen size of the pulverized coal entering the burners was in the range of 74% to 81% passing a 200 mesh screen. The pulverizers are expected to grind to 70% passing a 200 mesh screen. Pulverizer reject rates were not measured but are believed to be very low. The coal entering the pulverizer has been screened to a nominal 1-1/4 inch size.

3.1.7.3 Moisture Reduction

Relevant data are shown in Tables B-5, B-6, B-7 and B-8 and on Figure 3-8.

Moisture is liberated from the coal in significant quantities by the heated primary air during the pulverizing process. Weighted average moisture reduction was 49.3% during Test Series 1, 2 and 3 (see Figure 3-8). The

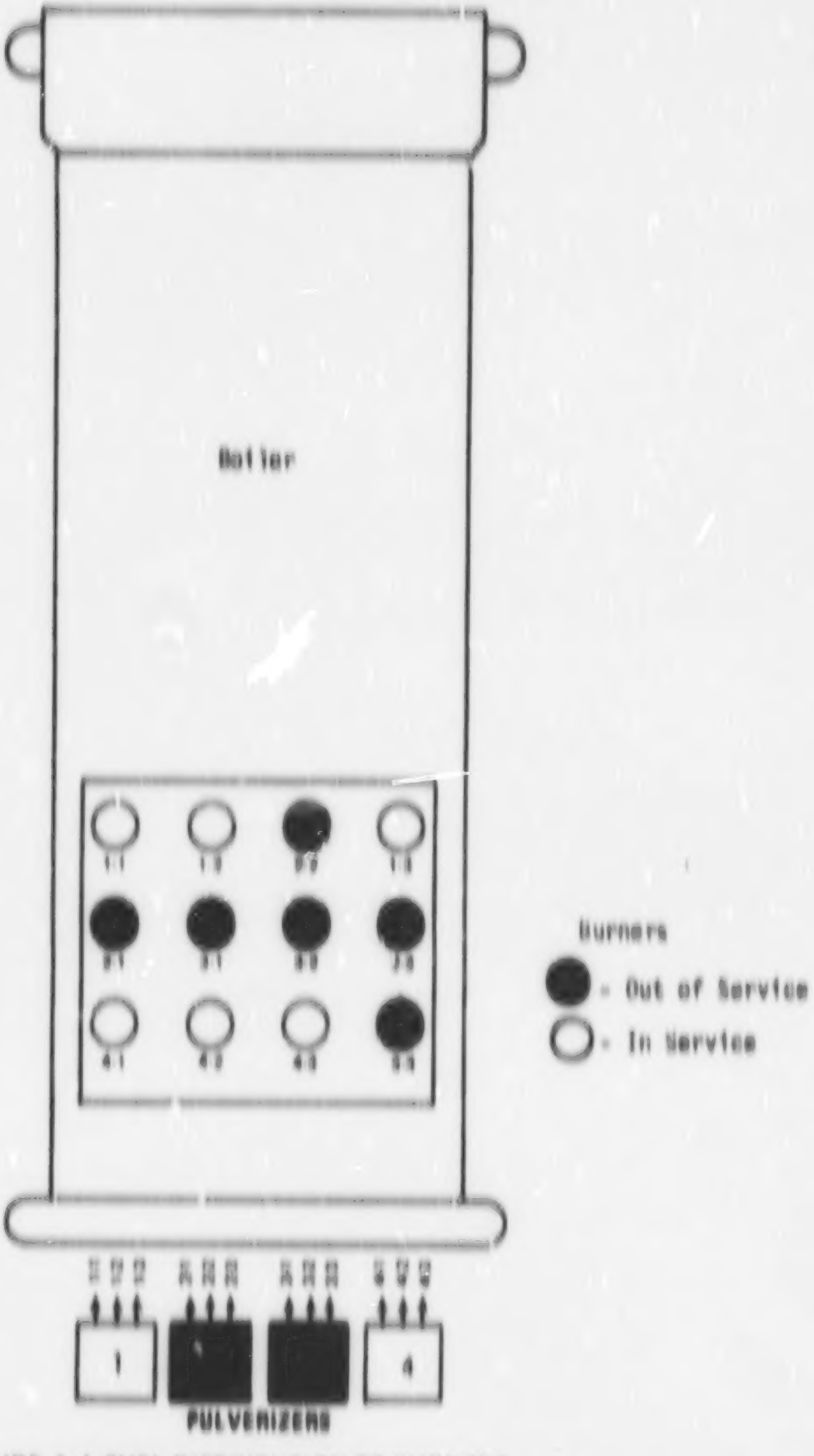

Boiler
Burners
● - Out of Service
○ - In Service
1
4
PULVERIZERS

FIGURE 3-4 FUEL DISTRIBUTION TO BURNERS
Test No. 1

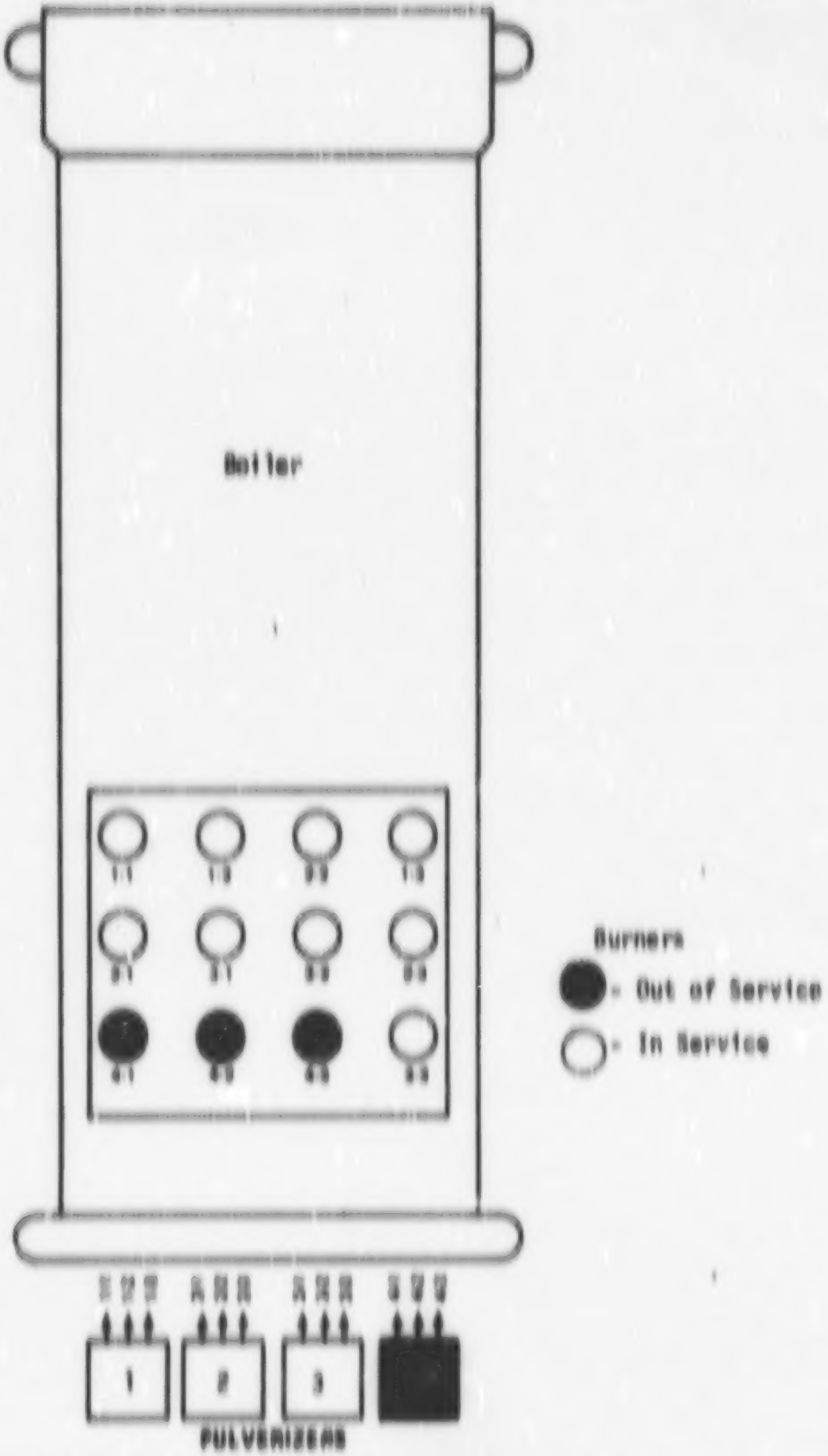

Boiler
Burners
● - Out of Service
○ - In Service
1
2
3
PULVERIZERS

FIGURE 3-5 FUEL DISTRIBUTION TO BURNERS
Test No. 16, 17

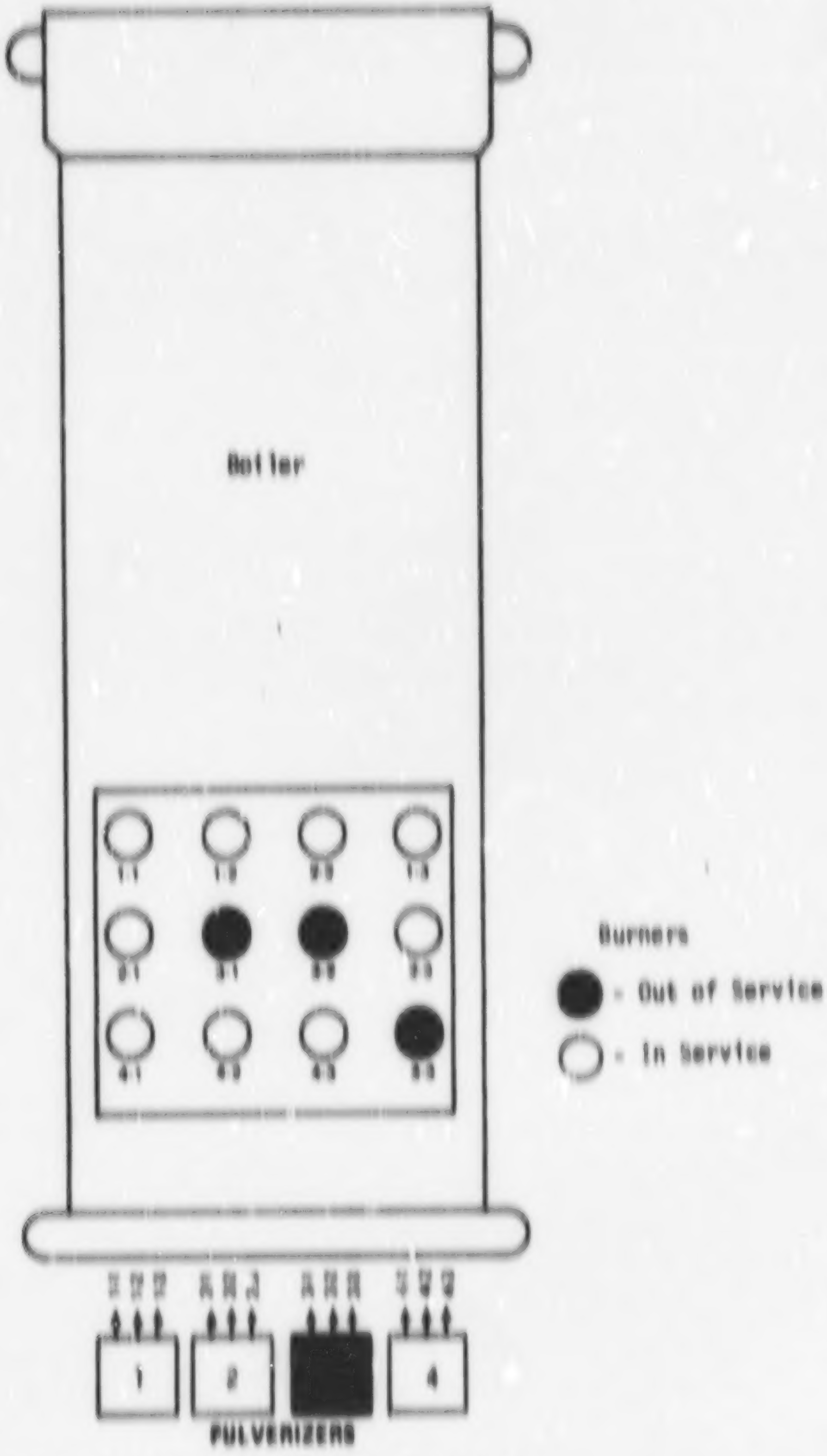

Boiler
Burners
● - Out of Service
○ - In Service
1
2
4
PULVERIZERS

FIGURE 3-6 FUEL DISTRIBUTION TO BURNERS
Test No. 2, 3, 4, 5, 6, 7

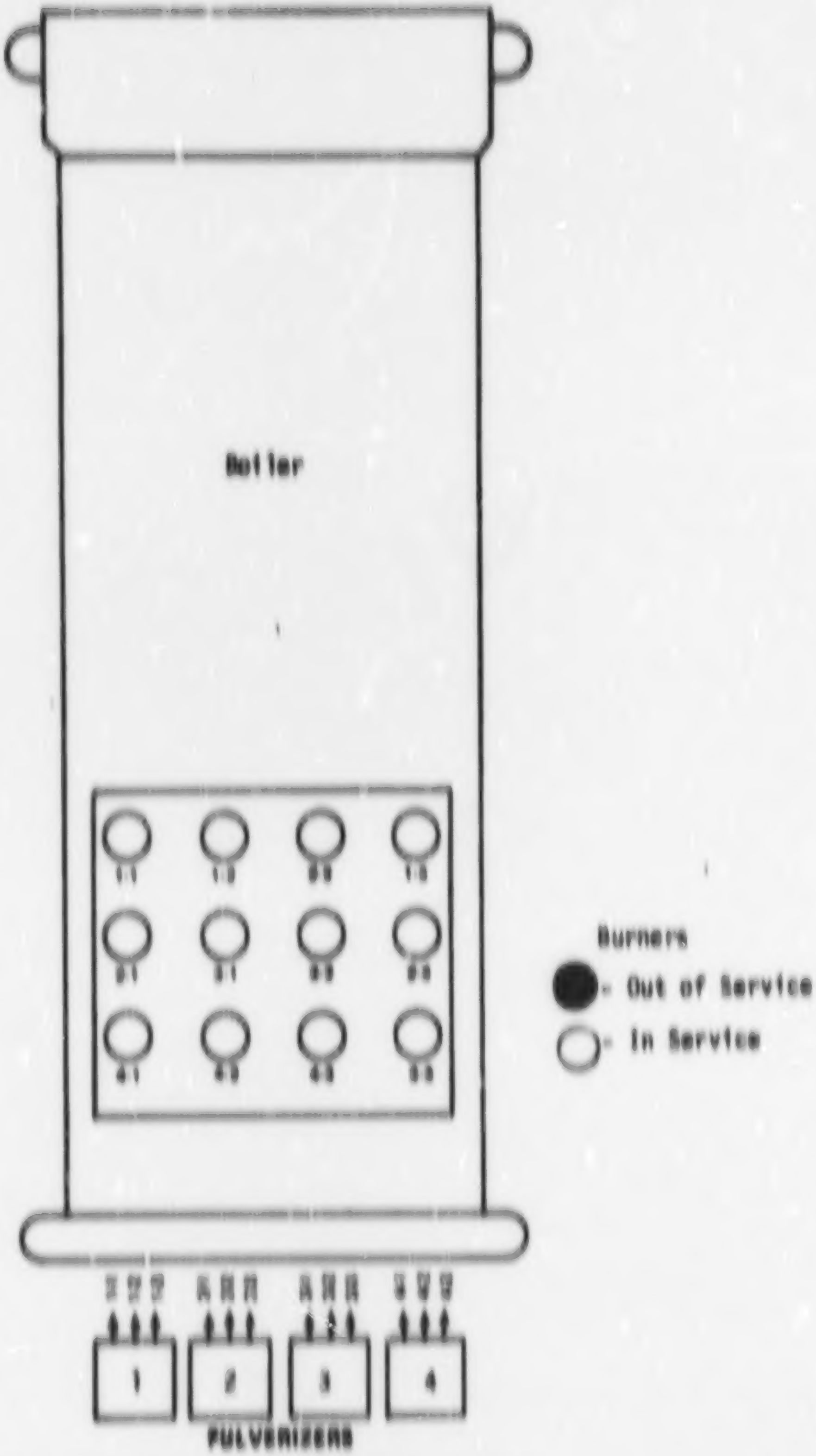
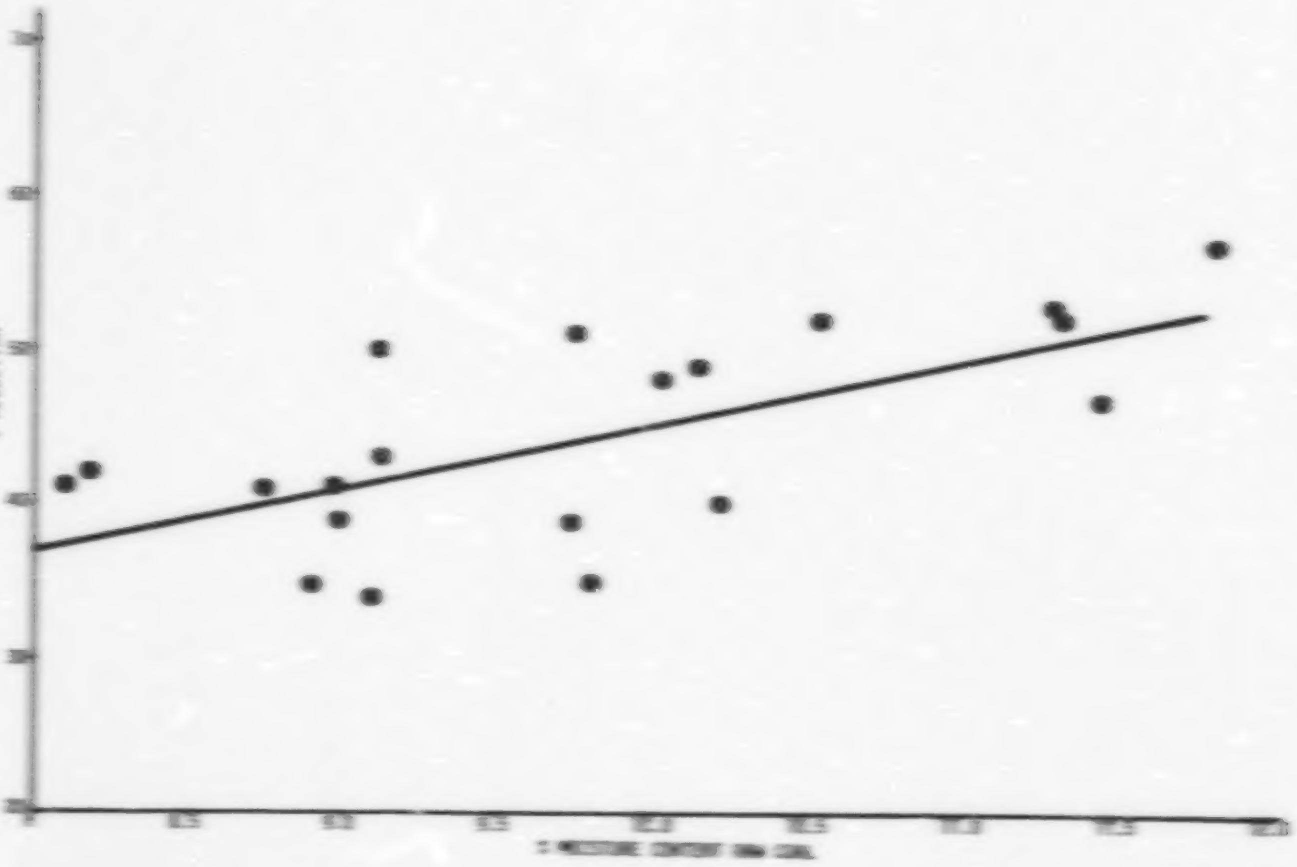

Boiler
Burners
- Out of Service
- In Service
1
2
3
4
PULVERIZERS

FIGURE 3-2 FUEL DISTRIBUTION TO BURNERS
Test No. 8, 9, 10, 11, 12, 13, 14, 15, 18, 19, 20, 21

FIGURE 3-8
% REDUCTION VS. % MOISTURE CONTENT IN RAW COAL
TEST SERIES 1, 2 & 3



magnitude of moisture reduction for individual tests was a function of the level of moisture in the raw coal. Higher levels of moisture in the raw coal probably reflect more surface moisture and thus the higher drying rate. The efficiencies and heat rates reported in 3.1.1 and 3.1.2 were calculated on the rates and compositions of the raw coal. Reduction in moisture content appeared to be independent of boiler load.

3.1.7.4 Power Requirements

Relevant data are shown in Tables B-11 and B-12 and on Figure 3-9.

The power requirements for driving the four primary air fans and the four pulverizers affect the net generating output of the boiler and thus its overall operating performance characterized by the net heat rate. The relative energy consumed is reported as the average current draw of each unit in Tables B-11 and B-12. Figure 3-9 shows the total power requirements, expressed in amps, for the primary air fan set and the coal mill set as a function of coal rate. Less power is required per ton of coal fired if fewer than four coal mills are utilized, but this changes the firing pattern as indicated earlier in the discussion.

3.1.8 Heated Air Requirements

3.1.8.1 Excess Air Levels

Relevant data are shown in Table B-13 and on Figure 3-10.

The amount of excess air is controlled to maintain 4% excess oxygen in the flue gas inlet the air preheater at steaming rates of 600,000 lb/hr. and higher and to maintain increasing concentrations of oxygen with decreasing load below 600,000 lb/hr. steaming rate, see Figure 3-10. For the 40MW load level, the excess air operating set point is about 6.2% oxygen in the flue gas. From 92MW to 115MW load level, the set point is 4.0% excess oxygen. The difference between the excess oxygen levels and the set point values during Test Series 1 and 3 is shown on Figure 3-10. The data are summarized as follows:

FIGURE 3-9
AMPS AS A FUNCTION OF COAL FEED RATE
TEST SERIES TWO

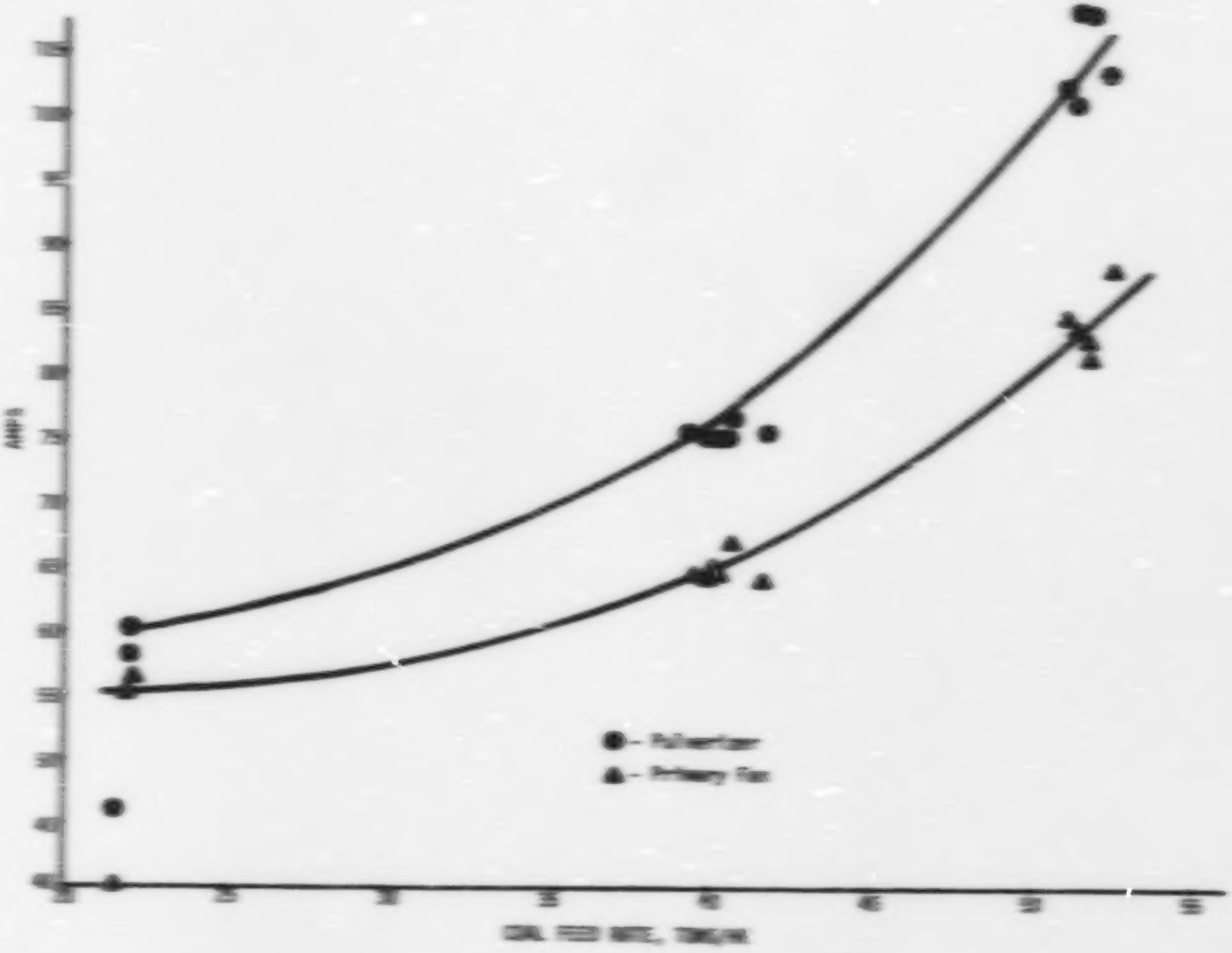
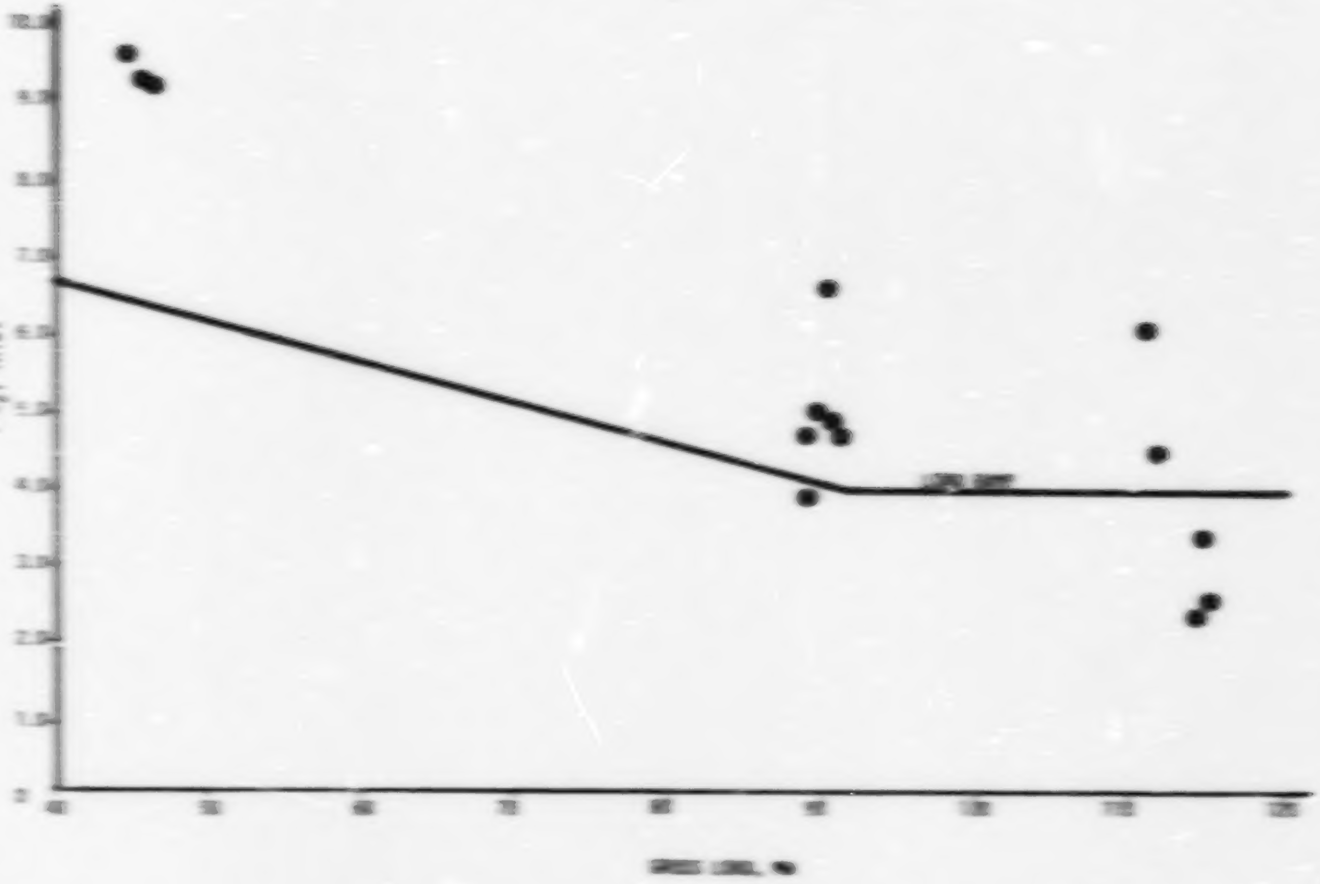


FIGURE 3-11
% O_2, INLET AIR HEATER vs. GROSS LOAD
TEST SERIES TWO



	% Oxygen	
	Actual	**Set Point**
46MW	9.3 - 9.6	6.2
92MW	3.9 - 6.6	4.0
111MW	4.5 - 6.1	4.0
118MW	2.4 - 3.4	4.0

The oxygen levels were consistently high only during the 46MW tests. The oxygen levels were either very near or above the set point during the 92MW and 111MW tests and were below the set point during the 118MW tests. The oxygen levels were determined from spot Orsat measurements by GC with thermal conductivity detection. The Mitchell station continuous oxygen analyzer was in service for only two tests (46MW) during Test Series 1.

3.1.8.2 Effect Of Excess Air On Efficiency

Relevant data are shown in Table B-13 and on Figures 3-10 and 3-11.

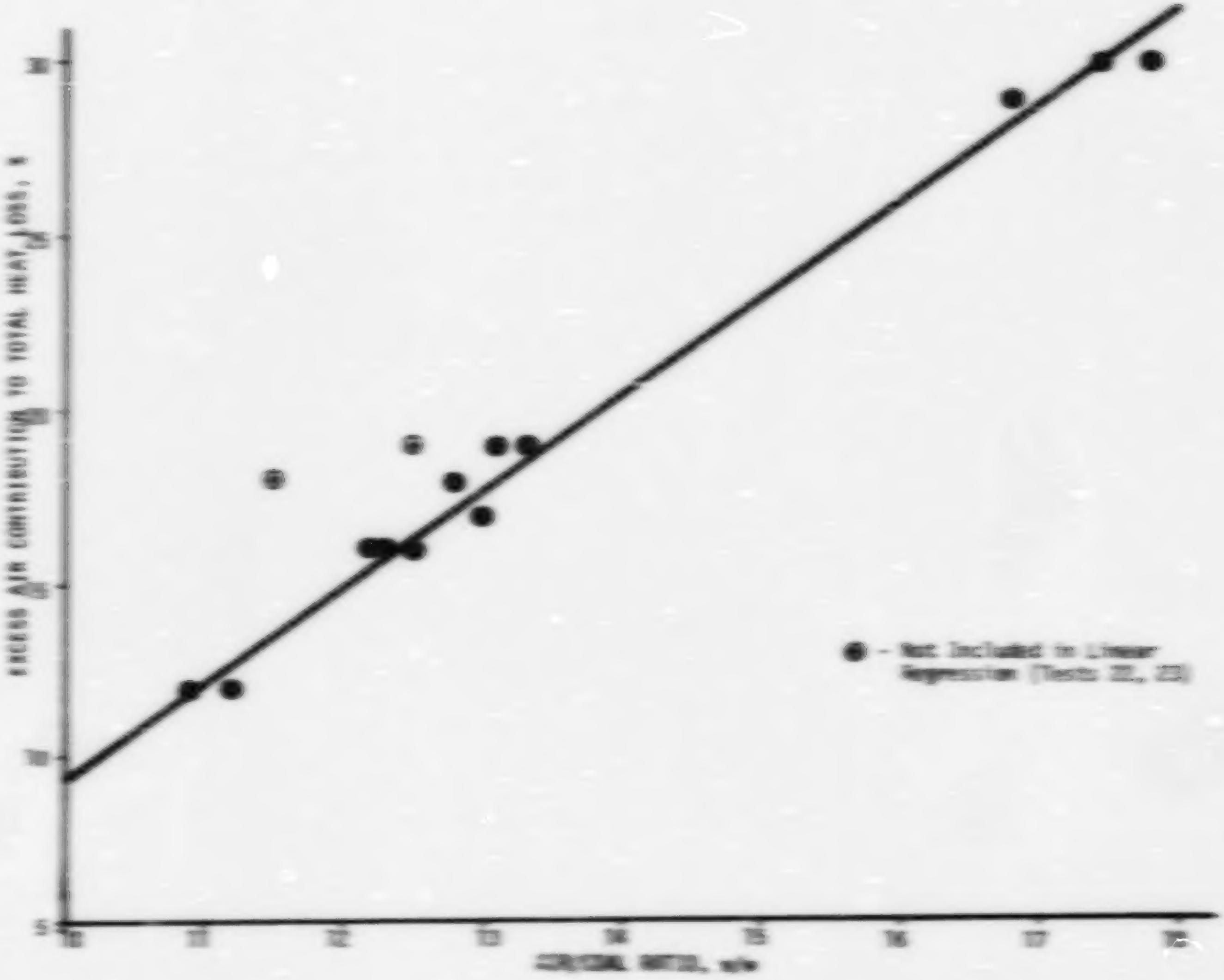
Excess air is a sink for the heat discharged to the stack and therefore contributes to the total heat loss and the resultant effect on efficiency. Even within the operating load settings, the contribution to the total losses from the excess air required to maintain complete combustion is substantial. Table B-13 and Figure 3-11 show these effects for Test Series 1. From 12% to 30% of the total heat loss was due to heat required for heating the excess air.

3.1.8.3 Air Heater Performance

Relevant data are shown in Table B-13.

The function of the air heaters is to recover heat from the flue gas through heat exchange with the incoming air. Performance data are summarized as follows:

FIGURE 3-11
EXCESS AIR CONTRIBUTION TO TOTAL HEAT LOSS vs. AIR/COAL RATIO
TEST SERIES TAG



Air ΔT Across Air Heater, °F	397
Heat Recovery, MMBTU/hr.	69-132
Heat Recovery, % of Total Heat Input	9.9-17.2
Air/Coal Ratio, w/w	10.9-17.8

Somewhat better heat recovery was experienced at 46MW over the heat recovery at 92MW and 115MW. At 46MW, the heat recovery varied from 14.6% to 17.2% whereas the heat recovery at the higher loads was in the range of 9.9% to 11.4%. This appears to be an effect of the higher excess air at loads below 92MW.

3.1.9 Boiler Drafts

Relevant data are included in Table 3-6 and Tables B-14, B-15 and B-16.

The boiler was designed for a total gas and air resistance of 10.7 inches W.C. pressure differential at full load between the FD fan discharge and air heater outlet. Table 3-6 summarizes the draft losses for the normal full load tests. The total resistance design value was exceeded during only one test (Test 10) of the three replicate test set. An excess draft loss of one inch W.C. was found, attributable to resistances on both the air and the gas side of the air heater.

3.1.10 Soot Blowing Effects

Relevant data are included in Table 3-1.

Tests with soot blowers operating were conducted during the 92MW (80% load) test set (Tests 2 thru 7) alternately with tests without soot blowing. Soot blowing normally requires about two hours but the period was extended to three hours during these tests to attain correspondence with the flue gas sampling period. There was no noticeable affect on efficiency and heat rate from soot blowing, see Table 3-1. The soot blower air compressor requires auxiliary power but it is not a major power user.

TABLE 3-8

DRAFT LOSSES AT 100% LOAD, in. W.C.

NORMAL OPERATING CONDITIONS

	Design	Test 8	Test 9	Test 10
Air, Air Heater	3.7	4.8	4.4	4.8
Ducts and Dampers A.P.H. to Burners, Burners and Windbox	3.2	1.5	2.0	2.5
Total Air Resistance	6.9	6.3	6.4	7.3
Furnace and Convection Banks	5.0	5.0	3.6	5.0
Flues to Air Heater	1.0	1.0	2.4	1.1
Gas, Air Heater	5.8	5.6	5.9	6.3
Total Gas Resistance	11.8	11.6	11.9	12.4
Total Boiler Resistance	18.7	17.9	18.3	19.7

3.2 FLUE GAS CHARACTERIZATION - NORMAL OPERATION

This section describes the results of a comprehensive test program for characterizing the outlet flue gas to:

- Establish pre-retrofit (baseline) performance of Mitchell No. 11.
- Provide a data base which can be used to compare this flue gas with the flue gas from other utility boiler configurations for which the WL/Allied process has applicability.
- Establish relationships betwenn flue gas parameters and boiler control settings in order to determine the effect, if any, of the retrofit on boiler operation and performance.
- Compare measured values of the flue gas parameters with the corresponding values upon which the design of the Demo. unit is based.

3.2.1 Scope Of Characterization

Tests were conducted to obtain a physical-chemical profile of the flue gas at normal operating conditions and at selected off normal operating conditions. Normal operation included an examination of effects on flue gas by varying the load from 40% to 100% and of soot blowing. Off normal operation included an examination of effects of high grain loading, excess combustion air, excess air inleakage, and low sulfur fuel.

The remainder of section 3.2 is devoted to a summary of the flue gas characterization results and to an evaluation of the data collected during normal operation and, as appropriate, off normal operation. The results and evaluations are presented as follows:

- A detailed physical-chemical profile is presented and summarized.
- Measured flue gas parameters are compared with the corresponding design parameters.

- Baseline emission levels are documented.
- Flue gas conditions are correlated with boiler control settings.
- Flue gas conditions having a potential effect on Demo. Unit performance are discussed.

3.2.2 Flue Gas Profile

Relevant data are included in Tables 3-7, 3-8, 3-9, B-17 and B-18.

Table 3-7 is a summary of the flue gas characterization data at normal operating conditions. This data provides the documentation of pre-retrofit (baseline) flue gas conditions. It also will be referenced in the succeeding subsections in which the flue gas characterization data is evaluated for each major pollutant, trace emissions, and physical characteristics.

The data has been examined to determine as far as possible which observations are outliers (invalid measurements). The outliers are not used in the correlations but the outlying observations are included in the tabulations and on the figures for correlating the flue gas properties with their independent variables. Examples of outliers are as follows:

Inlet flue gas mass rate - Test 2
Flue gas volume - Test 7
SO_2 mass rate - Tests 2, 9
NOx mass rate - Test 10
Particulate mass rate and grain loading - Soot blowing tests

3.2.3 Volume, Temperature, Pressure

3.2.3.1 Measured Volume Vs. Design

Relevant data appear in Tables 3-10, B-18 and Figures 3-12 and 3-13.

[illegible]

[illegible]

[illegible]

TEST NO.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
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TABLE 3-8

PARTICLE SIZE DATA
Normal Conditions

TEST NO.	LOAD GROSS (MW)	MASS MEDIAN DIAMETER (MICRONS)	SOOT BLOWING STATUS	AS FIRED COAL SIZE, % THRU 200 MESH
1	44.5	3.2	Off	--
2	90.3	2.9	Off	73.9
3	89.6	1.1	On	78.3
6	90.9	3.4	Off	78.6
10	114.9	1.4	Off	76.7

TABLE 3-9

PARTICLE SIZE DATA

Off-Normal Conditions

TEST NO.	LOAD GROSS (MW)	MASS MEDIAN DIAMETER (MICRONS)	SOOT BLOWING STATUS	AS FIRED COAL SIZE, % THRU 200 MESH
11	115.1	0.9	Off	73.7
12	114.7	1.5	Off	76.0
13	114.8	2.2	Off	79.3
18	108.9	3.0	Off	75.3

TABLE 3-10

THEORETICAL BOILER OPERATING PARAMETERS FOR CALCULATING FLUE GAS RATES

Coal Composition -	
- Ash, wt. %	9.89
- Sulfur, wt. %	3.15
- Hydrogen, wt. %	4.39
- Carbon, wt. %	61.18
- Moisture, wt. %	11.64
- Oxygen, wt. %	8.65
- Nitrogen, wt. %	1.09
- High Heating Value, Btu/lb	11299
Heat Rate, Btu/KWH, at -	
- 46MW	9604
- 69MW	9320
- 92Mw	9237
- 115MW	9247
Oxygen in Flue Gas, %, at -	
- 46MW	6.4
- 69MW	5.2
- 92MW	4.0
- 115MW	4.0

FIGURE 3-12
INLET (THEORETICAL & MEASURED) MASS RATE vs. GROSS LOAD
TEST SERIES I

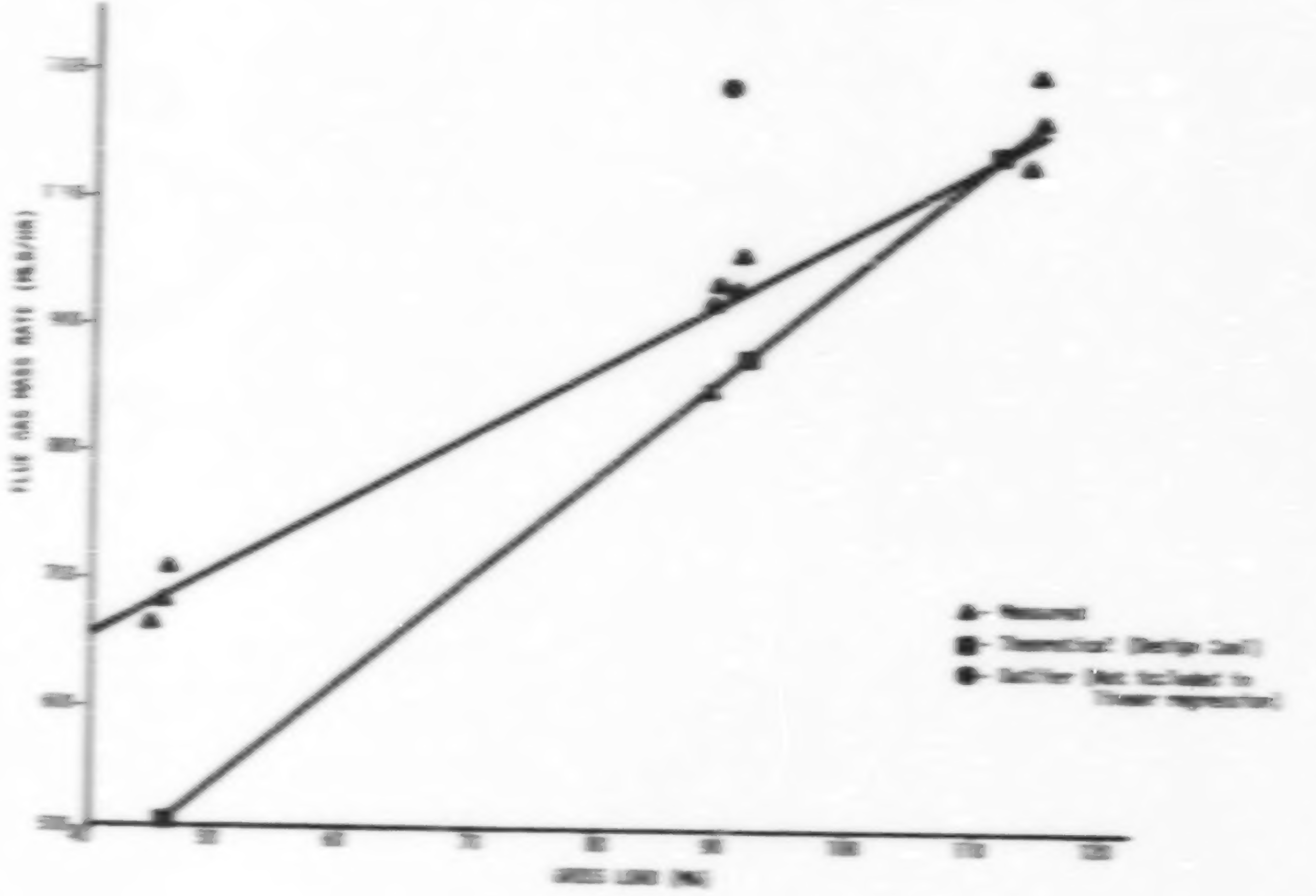
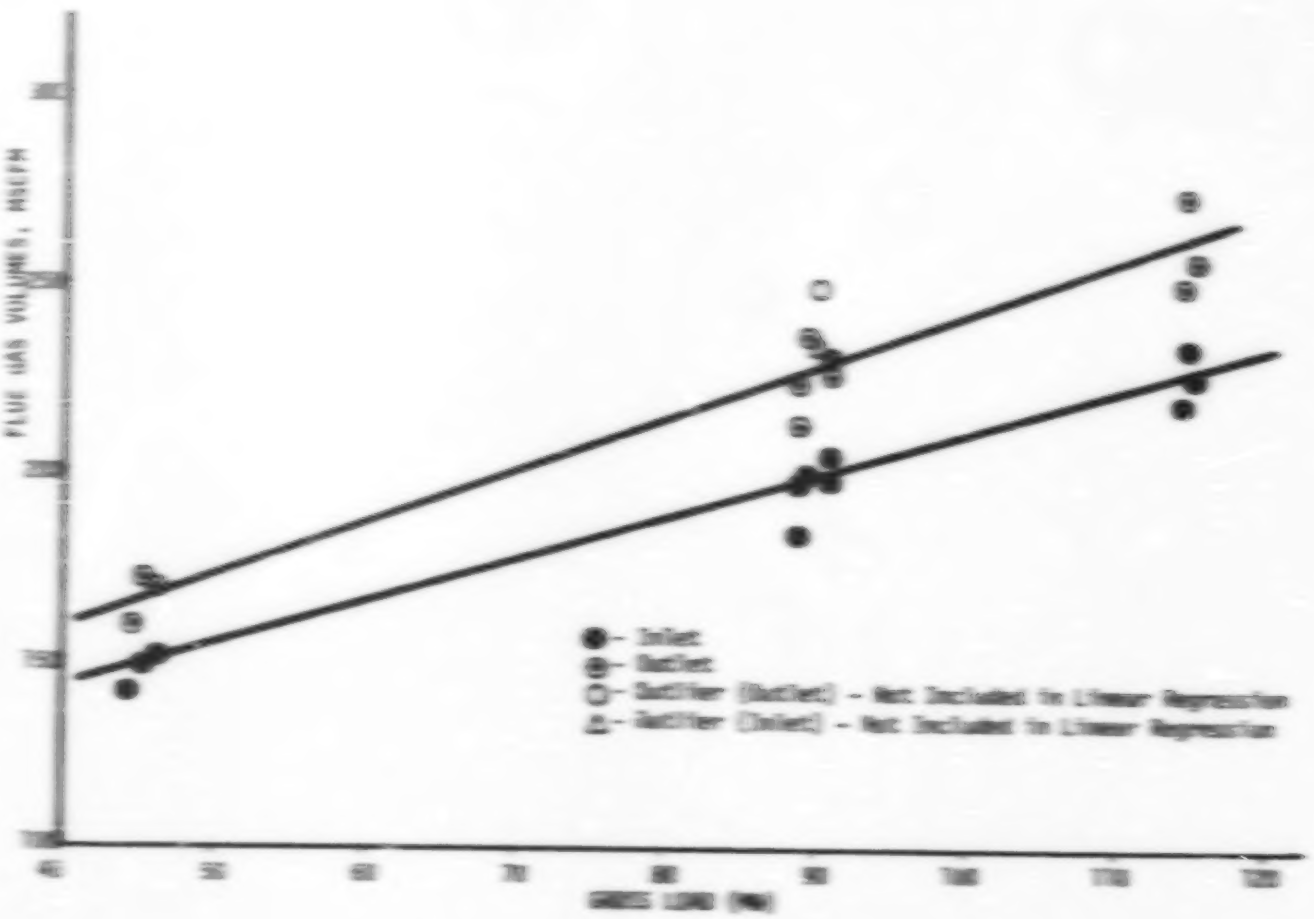


FIGURE 3-13
INLET & OUTLET FLUE GAS VOLUME FLOW RATE vs. GROSS LOAD
TEST SERIES 1



Measured flue gas mass rates are compared with the boiler design values over the range of operating loads on Figure 3-12. Predicted performance of the new boiler at full load, supplied by the boiler vendor, was extrapolated to other loads by calculation from the design coal composition, predicted heat rates and the excess oxygen values shown in Table 3-10. The theoretical flue gas rate is not a linear function of load. However, the degree of non-linearity is small and a linear function is assumed for presentation on Figure 3-12. Measured values at inlet the air heaters were in excess of design from 46MW to about 110MW. This is attributed to higher than design coal rates as affected by high heat rates and to higher than design excess air levels. High measured values at the outlet are additionally attributed to inleakage at the air heaters and beyond.

The Demo. Unit design flue gas rates at 92MW are 1.02 MMlb/hr. and 320,000 acfm (300°F, 14.7 psia). Baseline results at about 92MW averaged 1.10 MMlb/hr. and 336,000 acfm (268°F, 14.6 to 14.7 psia). Dry gas rates are also of interest as far as Demo. Unit operation is concerned. Demo. Unit design is based on dry gas rates of 0.98 MMlb/hr. at 92MW. Baseline data at 92MW averaged 1.06 MMlb/hr.

3.2.3.2 Flue Gas Rate Dependency On Boiler Control Settings

Relevant data are included in Table B-19 and on Figure 3-13.

Flue gas volume differences at the outlet are dependent primarily on coal rate and excess air. Additional independent variables might be coal moisture, carbon to hydrogen ratio and humidity of the air. Coal rate is dependent on the boiler efficiency. Excess air is also dependent on coal rate as well as on inleakage occurring primarily at the air heaters. Coal moisture and moisture in the air contributed about one to two percent of the total outlet flue gas. Carbon/hydrogen ratio was relatively constant. Its effect on flue gas volume was to increase it only three percent within the minimum and maximum limits of the carbon/hydrogen ratio. From 9% to 21% of the total flue gas was contributed by the excess air. Flue gas volume varied inversely with load factor. Figure 3-13 shows this dependency on load.

3.2.3.3 Temperature Vs. Design

Flue gas temperatures measured during the Baseline Test are listed in Table B-19. Examination of averages compared with boiler design values at the air heater outlet is presented as follows:

Avg. Gross Load, MW	Avg. Temperature °F	Design Temperature, °F, Corrected for Inleakage
45	275	---
61	---	276
90	289	---
115	320	286

The average temperatures measured at the outlet of the ID fans as a function of gross load were as follows:

Gross Load, MW	Temperature, °F
45	250
90	268
115	295

The Demo. Unit design specifications specify 300°F as the design temperature at a gross load of 92MW.

3.2.3.4 H_2SO_4 Condensation

Relevant data are shown in Tables 3-11 and 3-12.

Dew Points for H_2SO_4 condensation are determined graphically by the method of Martin, et. al.(3) In essence, this work correlates SO_3 concentrations with dew point temperatures as a function of the partial pressure of water in the flue gas. Martin's work indicates that below 100 ppm SO_3, dew point temperature changes with SO_3 concentration at a much reduced rate.

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Comparison of the dew point temperature with the minimum duct temperature indicates that there is probable H_2SO_4 condensation at 40% load conditions and possible H_2SO_4 condensation at 80% load. Minimum duct temperatures were usually found near the duct walls.

3.2.3.5 Pressures

Static pressures of the flue gas at inlet the air heaters and outlet the ID fans and the corresponding barometric pressures are tabulated in Table B-19 for Test Series 1.

3.2.4 Sulfur Oxides Emission Levels

3.2.4.1 Sulfur Mass Balance

Relevant data are included in Tables 3-7, 3-13, 3-14, and B-20.

The sulfur balance across the boiler was in excess of full closure by about 12% for the tests in which 3% sulfur coal was burned. Closure averaged about 108% for the tests in which one percent sulfur coal was burned. The mass balance was computed by equating sources and sinks. The sole source was assumed to be the sulfur content of the coal, since the highest expected concentration of sulfur in the ambient air would contribute only negligible amounts. The sulfur sinks are:

- SOx in flue gas
- S in rejects
- S in bottom ash
- S in fly ash

Normally, sulfur in the rejects, bottom ash, and fly ash account for about 5% of the input. The sulfur mass balance of these tests includes only an estimate of sulfur in the fly ash and the measured SOx in the flue gas, calculated as follows:

TABLE 3-13

SULFUR MASS BALANCE, LB/HR

Test No.(1)	S_{in}	S_{out}	% Closure	diff	% diff
1	1426	1535	107.6	109	7.4
16	1408	1606	114.1	198	13.1
17	1414	1612	114.0	198	13.1
2	2675	1725	64.5	-950	-43.2(2)
3	3101	3028	97.6	-73	-2.4
4	2680	3289	122.7	609	20.4
5	2212	2866	129.6	654	25.8
6	2418	2377	98.3	-41	-1.7
7	3055	2858	93.6	-197	-10.1
8	3322	3655	110.0	333	9.5
9	3360	5412	161.1	2052	46.8(2)
10	3290	3990	121.3	700	19.2
11	3251	3482	107.1	231	3.4
12	3066	3526	115.0	460	14.0
13	3522	4216	119.7	694	17.9
28	902	2074	229.9	1172	78.8(2)
29	1150	1018	88.5	-132	-12.2
30	1026	698	68.0	-328	-38.1(2)
31	615	762	123.9	147	21.4
32	657	776	118.1	119	16.6
34	987	987	100.0	0	--

(1) Tests 1-17, 3% S coal. Test 28-34, 1% S coal.

(2) Outlier values.

TABLE 3-16

SULFUR BALANCE EFFECTS

	Observed (At 112% of Closure)	Corrected to 100% Closure
SO_2 at 92MW, lb/hr average	5335	4763
SO_2 at 92MW, lb/hr range	4381-6107	3912-5453
SO_2 at 92MW, ppmv average	2384	2129
SO_2 at 92MW, ppmv range	1952-2679	1743-2392
SO_2 All Tests, ppmv range	1742-2800	1555-2500
SO_3 at 92MW, ppmv average	58	52
SO_2 + SO_3 at 92MW, lb/hr average	5135	4585
Lb SO_2/MMBTU, average All Tests(1)	5.9	5.3

---

(1) Excluding outliers.

$$\%\ \text{Closure} = \frac{S_{\text{flue gas}} + S_{\text{ash}}}{S_{\text{coal}}} \times 100$$

where:

$$S_{\text{coal}} = \frac{\text{lb S}}{\text{lb coal}} \times \text{coal rate}$$

$$S_{\text{flue gas}} = 0.5 \times \frac{\text{lb } SO_2}{\text{hr.}} + 0.4 \times \frac{\text{lb } SO_3}{\text{hr.}}$$

$$S_{\text{ash}} = \frac{\text{lb S}}{\text{lb ash}} \times \frac{\text{lb ash}}{\text{lb coal}} \times \text{coal rate}$$

Table 3-13 shows the mass balance for tests on which complete data are available (sulfur in ash was not measured for every test). For the high sulfur tests during which closure exceeded 100%, possible errors may be in the flue gas volume measurement, sample metering, or in the analytical standards used. Any errors associated with the sulfur mass balance are likely to be in combination since any single source of error is not expected to be large enough to contribute an average of 12% or more of the total sulfur. Major errors in the inlet sulfur parameters are discounted. Sulfur in coal values agree with those expected. A substantial coal rate error is not reasonable because it would result in lower than reasonable boiler efficiencies. The coal scales were recalibrated prior to these tests and different analytical standards were used for the low sulfur tests.

In the discussion to follow on sulfur oxide emissions, the results will be discussed with the assumption of no closure error. The data presented in the tables and figures assumes no closure error. To have a common basis for comparison with later tests to be conducted during the Demonstration, the more important results are corrected to 100% closure basis and presented in Table 3-14.

3.2.4.2 Measured SO_2 vs. Design SO_2

Relevant data are included in Tables 3-7, B-20 and on Figures 3-12 and 3-14.

FIGURE 3-14

SO_2 EMISSIONS (THEORETICAL & MEASURED) vs. GROSS LOAD

TEST SERIES I

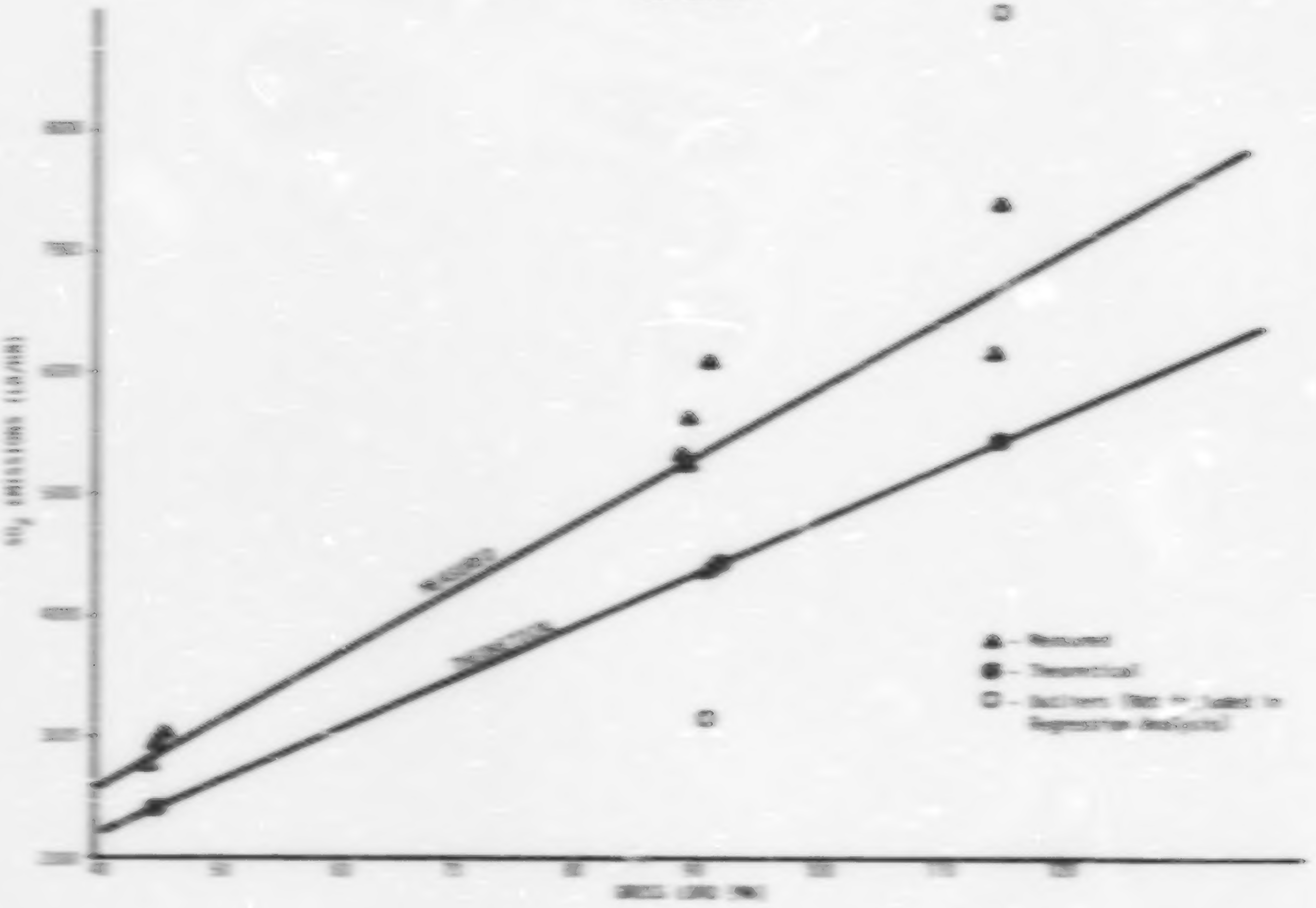


Figure 3-14 compares the measured SO_2 emissions with theoretical emissions which are based on design basis coal composition. Linear regression techniques were used to plot the SO_2 emissions as a function of load. Figure 3-14 shows that SO_2 mass emission rates were 20% higher than the theoretical basis emission rates used for boiler design. These effects are due to higher than design coal rates which are due to less than design boiler efficiencies, slightly higher than design coal sulfur, and other fuel composition effects.

The WL/Allied Demonstration Unit design was based on the following expected conditions:

Gross Load (MW) : 92 (80% load)

S in Coal (wt. %) : 3.2

SO_2 in flue gas (ppmv) : 2105

SO_2 in flue gas (lb/hr) : 4842

SO_3 in flue gas (ppmv) : 35

SO_3 in flue gas (lb/hr) : 97

Baseline Test data at normal operating conditions and 92MW averaged about 5574 lb/hr SO_2 or about 15% higher than design. Individual test results varied from 5243 lb/hr to 6107 lb/hr. The data scatter is discussed in subsection 3.2.4.3. Concentration of SO_2 is an equilibrium driving force in the absorption step of the WL/Allied process. At an average of 90MW for six tests, the concentration of SO_2 averaged 2493 ppmv compared with 2105 ppmv design concentration at 92MW. The individual concentrations varied from 2373 ppmv to 2679 ppmv. Over the full operating load range, the individual concentrations varied from 1742 ppmv to 2863 ppmv. The greater variations in the latter case are due to the effect of load on flue gas volume. At 92MW, concentration of SO_3 was 52 ppmv average compared to 35 ppmv used for the Demo. Unit design. Total sulfur (SO_2 + SO_3) rates averaged 5742 lb/hr.

3.2.4.3 Sulfur Dioxide Emissions Compared to the New Source Performance Standard

For solid fossil fuel, the standard requires that emissions of 1.2 lbs SO_2/MMBTU not be exceeded. Measured rates at normal operating conditions averaged 6.1 lbs SO_2/MMBTU. Based on these data, absorber efficiencies of better than 80% are required to keep SO_2 emissions below the New Source Standard.(4) (The above comparison is not made to show whether or not Mitchell No. 11 is in compliance with an applicable standard. Throughout the Test and Evaluation program, emissions will be compared with the applicable National standards only for the purpose of illustrating one facet of applicability of the WL/Allied process to the total population of utility boilers).

The standard deviation from the mean was ± 0.4 lbs SO_2/MMBTU, after rejection as outliers of the data of Tests 2 and 9. There was no apparent variation with load in the emission rate values when expressed as lbs SO_2/MMBTU. Values which exceeded two standard deviations were rejected as outliers.

3.2.4.4 Dependency on Load

Relevant data are shown in Table B-20 and on Figures 3-14 and 3-15.

The mass rate of SO_2 correlated linearly with gross load and with heat input according to the following relationships:

$$y = 55.5\ x + 379.5$$

$$y = 5.956\ x' - 40.69$$

where:

y is SO_2 emission in lbs/hr

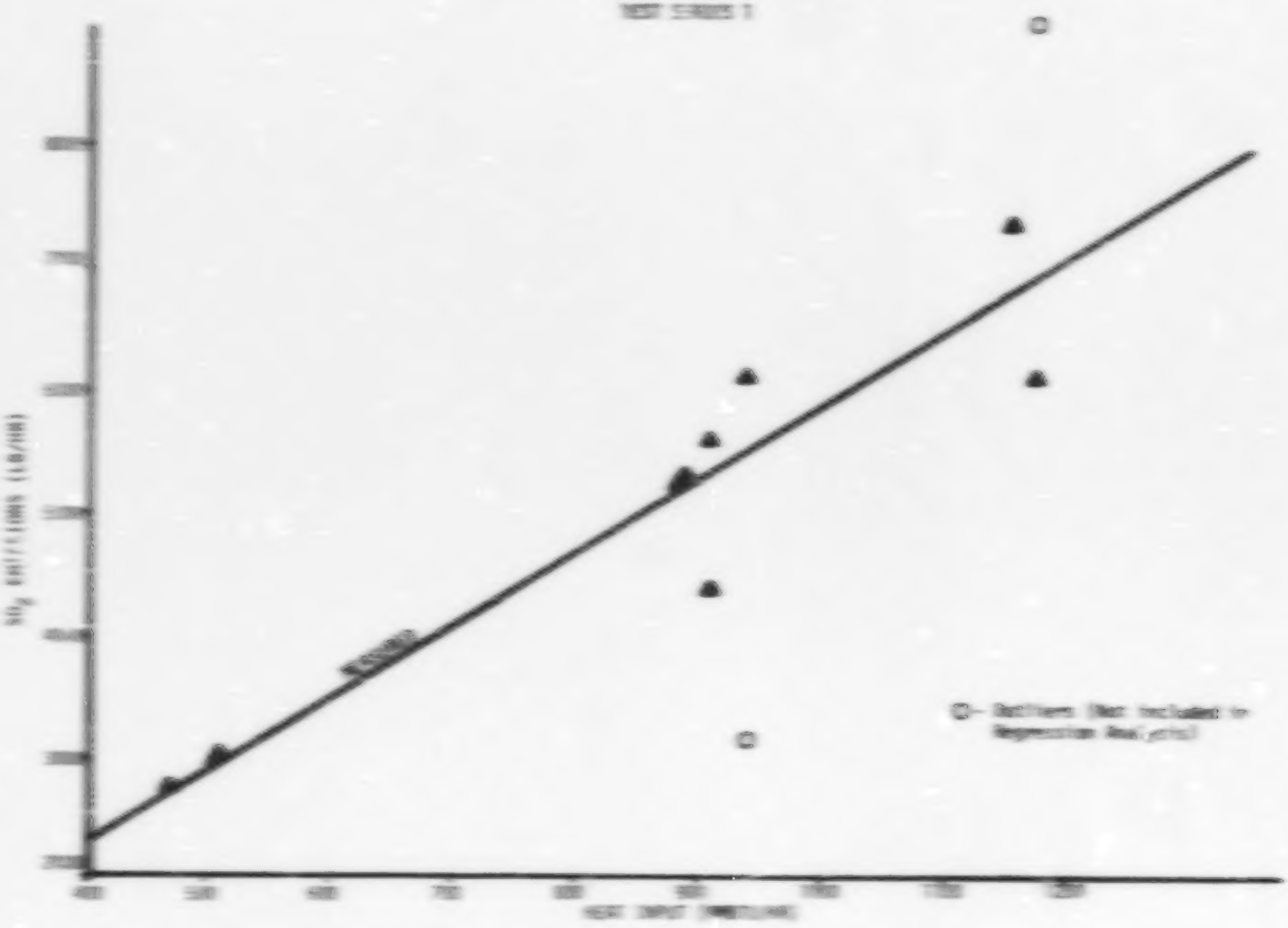
x is gross load in megawatts

x' is heat input in MMBTU/HR

The data of Tests 2 and 9 were rejected as outliers, see 3.2.4.3.

Concentrations of SO_2 and SO_3 in the flue gas increased with increasing load from 46MW to 92MW.

FIGURE 3-15
MEASURED SO_2 EMISSIONS vs. HEAT INPUT
TEST SERIES 1



3.2.4.5 Dependency on Other Boiler Control Settings

Relevant data are included in Tables 3-4 and B-20.

Other independent variables with the potential for affecting SO_2 emissions are sulfur in coal and excess air levels. Confidence limits (95%) of sulfur in the coal were 3.90% sulfur to 4.26% sulfur (dry, ash free basis), see Table 3-4. Based on those confidence limits, at a coal rate of 103,800 lb/hr, the true mean input sulfur would be expected to be within the limits of 3200 lb/hr to 3500 lb/hr with a corresponding variation in the true mean emission rate of sulfur. As an approximation, the mean emission rate as SO_2 would not be expected to vary beyond the limits of 6400 lb/hr to 7000 lb/hr at full load.

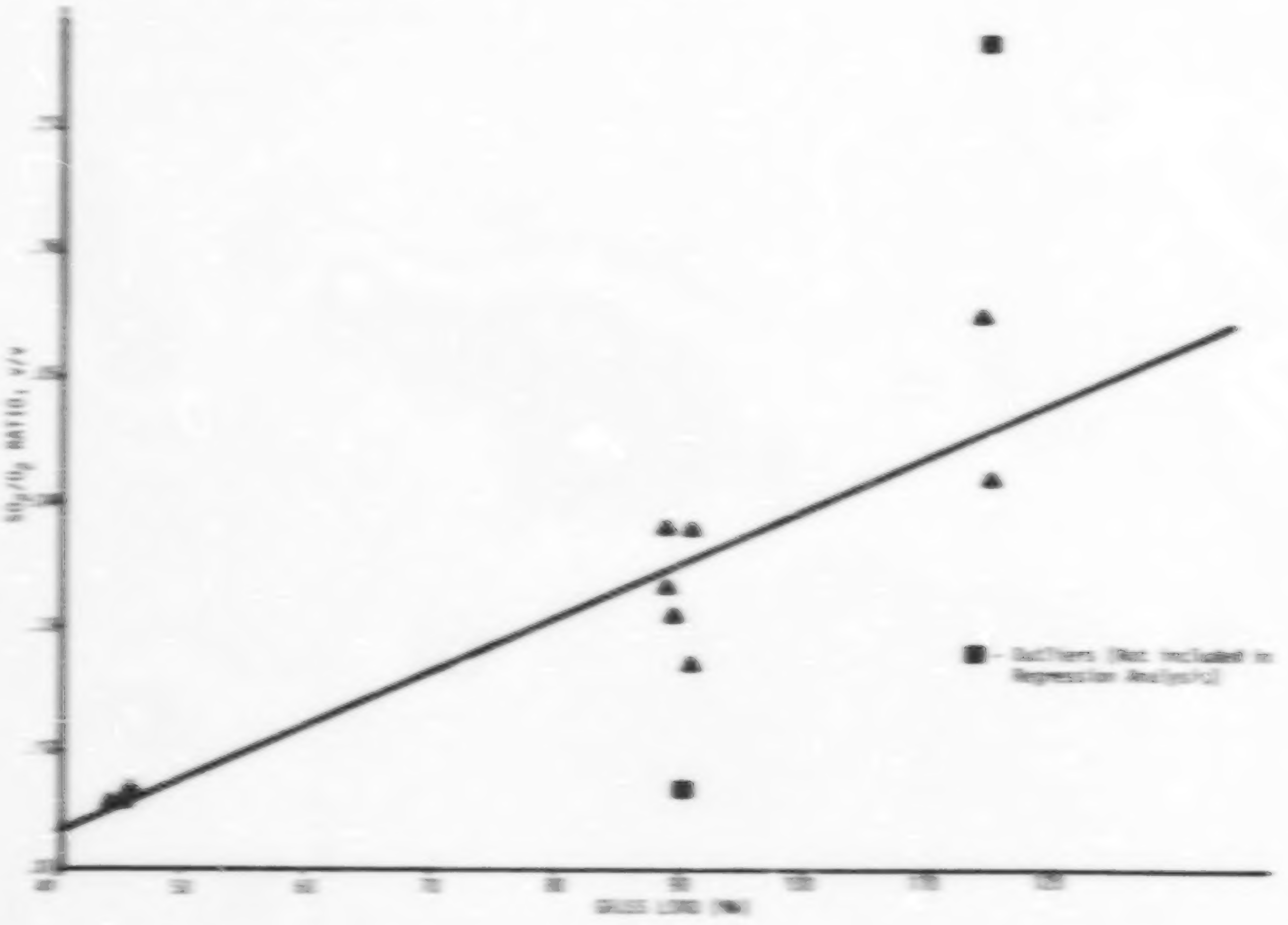
Excess air will affect emission concentrations due to dilution effects. The major effects on SO_2 concentrations were excess air and load factor. At the 46MW load level, $SO_2 + SO_3$ concentrations averaged 1827 ppmv versus 2548 ppmv at 92MW and 2834 ppmv at 115MW. The major effect appears to be from dilution by excess air.

3.2.4.6 Potential Effects on Demo. Unit Operation

Relevant data are included in Tables B-20, B-21 and on Figure 3-16.

Increasing levels of sulfur trioxide (SO_3) entering the absorber with the flue gas will form more sulfate in the absorber solution which will require higher purge rates. Higher oxygen levels could result in the formation of more of the inactive sodium salts in the absorber solution, which would in turn result in higher purge rates or higher antioxidant feed rates with subsequent higher raw material costs. Table B-20 shows ratios of SO_3 and of oxygen to SO_2. The observed SO_3/SO_2 ratios are summarized as follows:

FIGURE 3-18
SO_2/O_2 vs. GROSS LOAD
TEST SERIES 1



Load	SO_3/SO_2
46MW	0.033
92MW	0.022
115MW	0.025

The boiler is operated at higher combustion air levels at loads below 92MW. Also, there may be temperature differences in the furnace affecting reaction rates at varying loads. An attempt was made to show the effect of increased combustion air on the SO_3/SO_2 ratio by running a set of special tests during which an excess over normal of combustion air was used. The results are summarized as follows:

		SO_3/SO_2	
	Test No's.	Normal	Off Normal
	8, 14	0.011	0.034
	15	--	0.033
	10, 16	0.039	0.018
Mean		0.025	0.028
Mean Excess Combustion Air, %		15	26
Mean Gross Load, MW		114.7	109.7

While the off-normal mean of the SO_3/SO_2 ratio is slightly larger than the mean of that ratio at normal operation, the hypothesis that excess air increases the SO_3/SO_3 ratio can only be claimed to a confidence level of 67% on the basis of this data. This is far below the classical 95% or 99% confidence level usually required in making a definite conclusion.

Ratios of SO_2/O_2 are shown on Figure 3-16 as a function of load at normal operation. As expected, oxygen levels relative to the SO_2 levels increase with decreasing load factor.

The results from the special tests during which an excess over normal of combustion air was used showed no decrease in the SO_2/O_2 ratio when compared with results during normal operation.

3.2.5 NOx Emission Levels

Relevant data are found in Table 3-7.

Table 3-7 lists the volumetric concentration and mass emission rates for Test Series One (normal operation). Design values for NOx emissions were not available. Thus, discussion of the results has been limited to comparison with the emission standard, dependence on boiler control settings, and potential effects on Demo. Unit performance.

3.2.5.1 NOx Emissions Compared to the New Source Performance Standard

The emission standard for solid fossil fuel is 0.7 pounds per million Btu heat input. NOx emissions were below this standard for all of the tests at normal operation. The data of one test, at full load level, was rejected as an outlier based on emissions (lb NOx/MMBTU) being greater than two standard deviations from the calculated mean.

3.2.5.2 Dependency on Boiler Control Settings

The mass emission rates are expected to be dependent primarily on load and on excess air. The rates increased with load and decreased with excess combustion air during tests at normal operation, see Table 3-7. However, since excess air is controlled at higher rates for the lower load levels, it is possible that the variations in NOx rates are due entirely to load effects.

3.2.5.3 Potential Effects on Demo. Unit Performance

The oxidizing character of nitrogen dioxide (NO_2) may result in the formation of inactive sodium salts in the absorber in addition to potential formation from excess oxygen in the flue gas (see 3.2.4.6). In Table 3-7, concentrations of nitrogen oxides are expressed as the mol ratio, NOx/SO_2. No variation of this ratio with variations of excess combustion air is apparent from examination of these data. It should be noted that the NOx used in the ratio is the total mols of nitrogen oxides assumed to be NO_2 when in fact the NOx is expected to include some nitric oxide (NO). The NO is readily oxidized but the rate of formation of NO_2 in the flue gas is said to be very low, resulting in only 5%-10% of the NOx as NO_2 at the stack outlet(5). The oxidizing potential for NO is significantly lower than that for NO_2. Thus, the NOx/SO_2 ratio will serve as only a general indication of the potential for oxidizing effects.

The formation of NO is dependent on firing temperatures and on the concentration of oxygen within the flame zone of the boiler. Thus, one would predict that a variation in the excess air for combustion would cause a variation in NOx formation. The effect of increased combustion air was examined by running a set of special tests at full load. The results are summarized as follows:

	a Test No's.	NOx/SO_2 Normal	 Off Normal
	8, 14	0.047	0.021
	9, 15	0.025	0.019
	10, 16	0.086	0.039
Mean		0.053	0.026
Mean Excess Air, %		15	25

The decrease in relative NOx concentration with an increase in excess air was unexpected. A possible explanation is that the NOx concentration may be dependent on the change in operating procedure employed to increase the excess air level.

3.2.6 Particulate Emissions

3.2.6.1 Scope

Particulate matter was sampled simultaneously at both the inlet to the air preheaters and the outlet of the ID fans. Particulate sampling and analyses were done in accordance with Federal Register(6) methods at the outlet and ASME(7) methods inlet and outlet. ASME sampling at the inlet was necessary because of the high grain loadings expected. ASME sampling at the outlet was performed to obtain corresponding data for evaluating precipitator (ESP) performance.

3.2.6.2 Comparison with Boiler and Demo. Unit Design

Relevant data are shown in Table B-22 and on Figures 3-17, 3-18 and 3-19.

The Mitchell No. 11 design is based on coal containing 9.89 wt. percent ash. Boiler specifications assume that 10% of the total ash is collected ahead of the air heater outlets. ESP is designed to be 98.5% efficient. Because of dust configuration, sampling ports at the air heater outlets could not be used. Thus, particulate emissions were measured at the inlet duct to the air heaters. To calculate theoretical emissions, design coal ash content of 9.89%, 90% of total ash at the air heater inlet, and an ESP efficiency of 98.5% were assumed.

Figures 3-17, 3-18, and 3-19 compare measured emission rates with the corresponding theoretical values over the operating load range. Without soot blowing, measured particulate rates before the precipitator were lower than theoretical rates by as much as one-third. However, inlet particulate matter was sampled by the ASME method only. Clasically, the ASME method gives lower results than those obtained with approved EPA methods; this phenomena may be observed by comparing ASME method results obtained at the outlet with EPA method results obtained simultaneously at the same sampling position. Average particulate emission rates by the EPA method are almost double the average results obtained by the ASME method. With soot blowing, the particulate

FIGURE 3-17
PARTICULATE EMISSIONS (LB/HR) INLET APH vs. GROSS LOAD
TEST SERIES 1 & 3

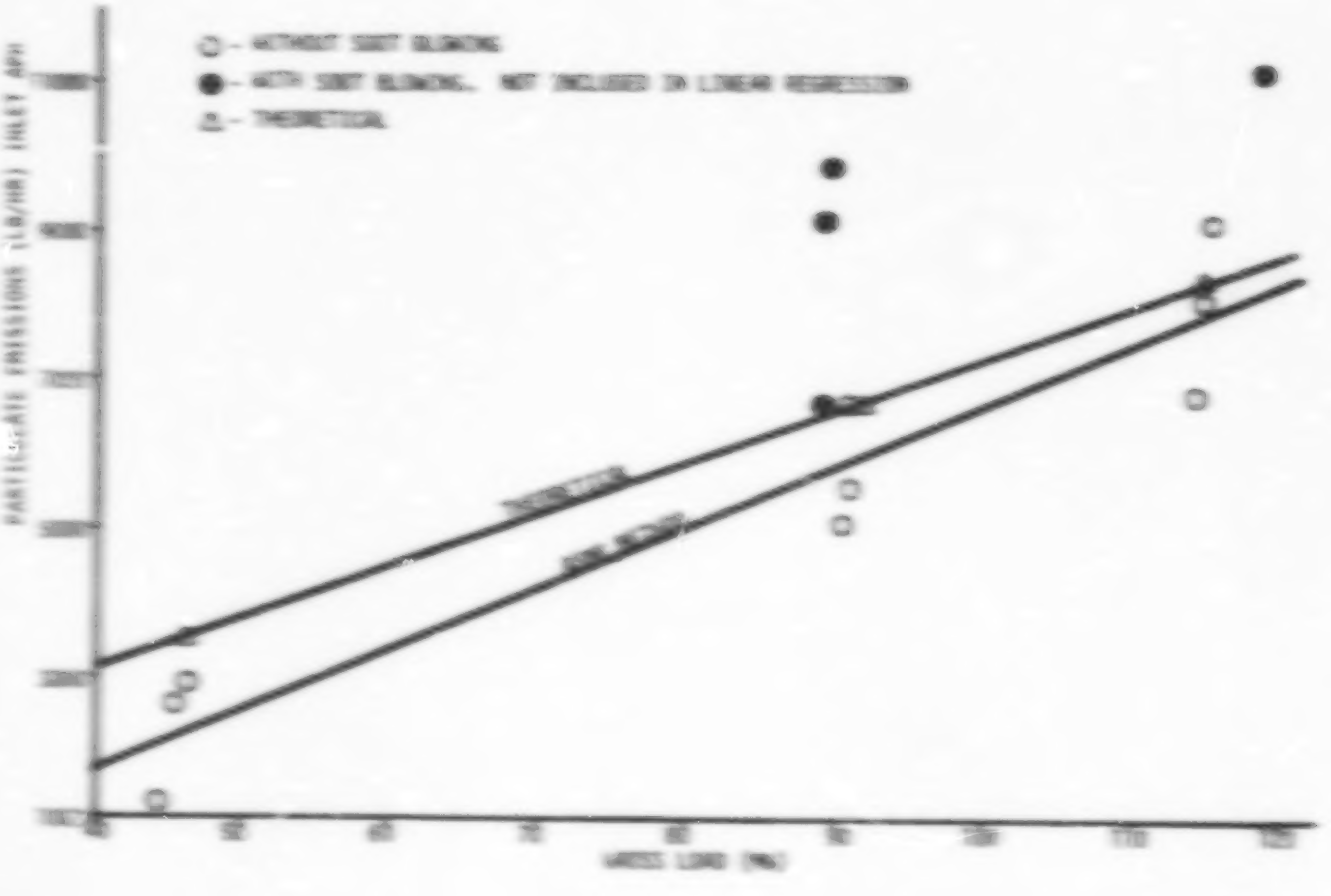


FIGURE 3-18
PARTICULATE EMISSIONS LEAVING OUTLET (LB/HR) vs. GROSS LOAD
TEST SERIES 1 & 2

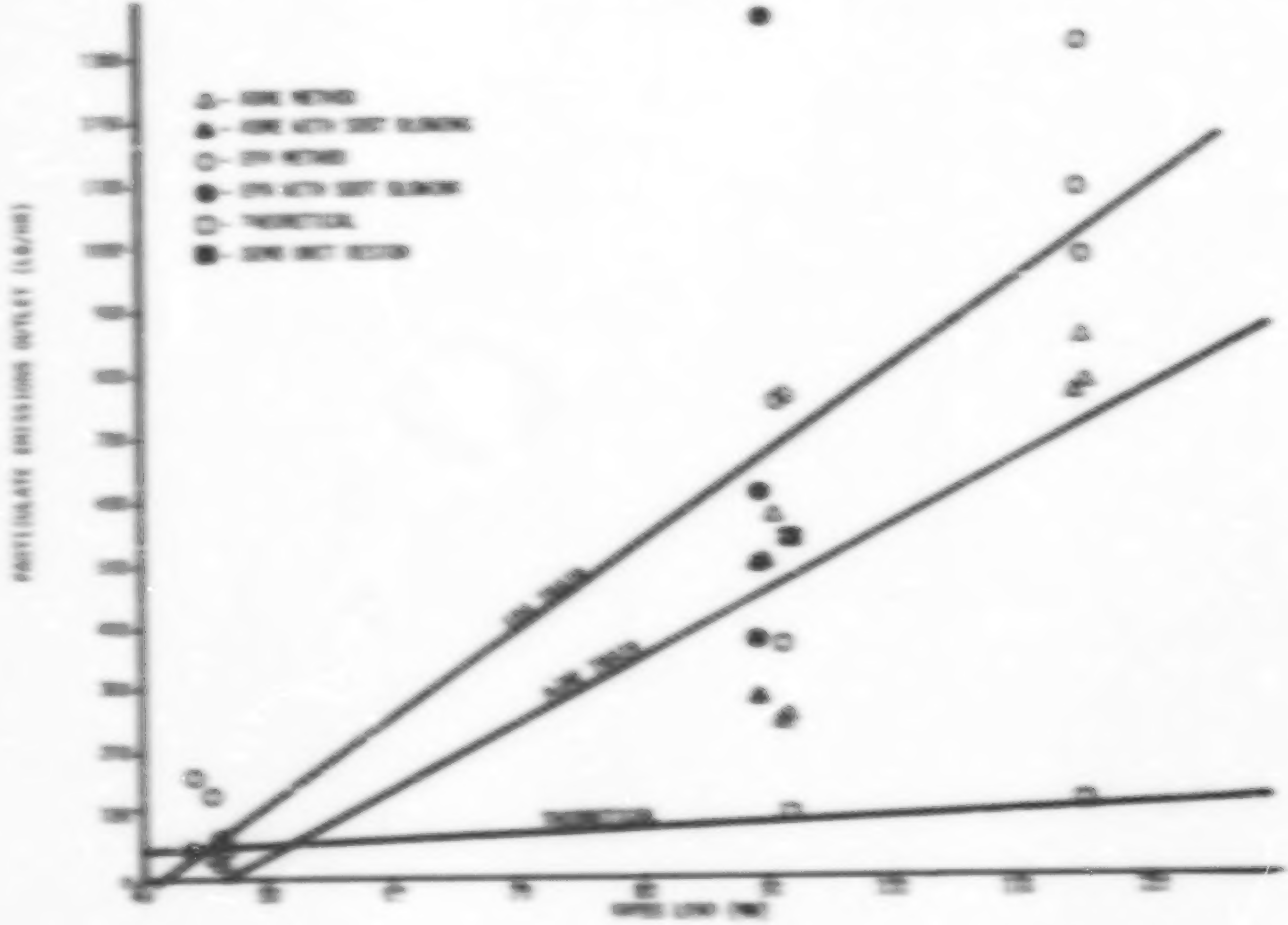
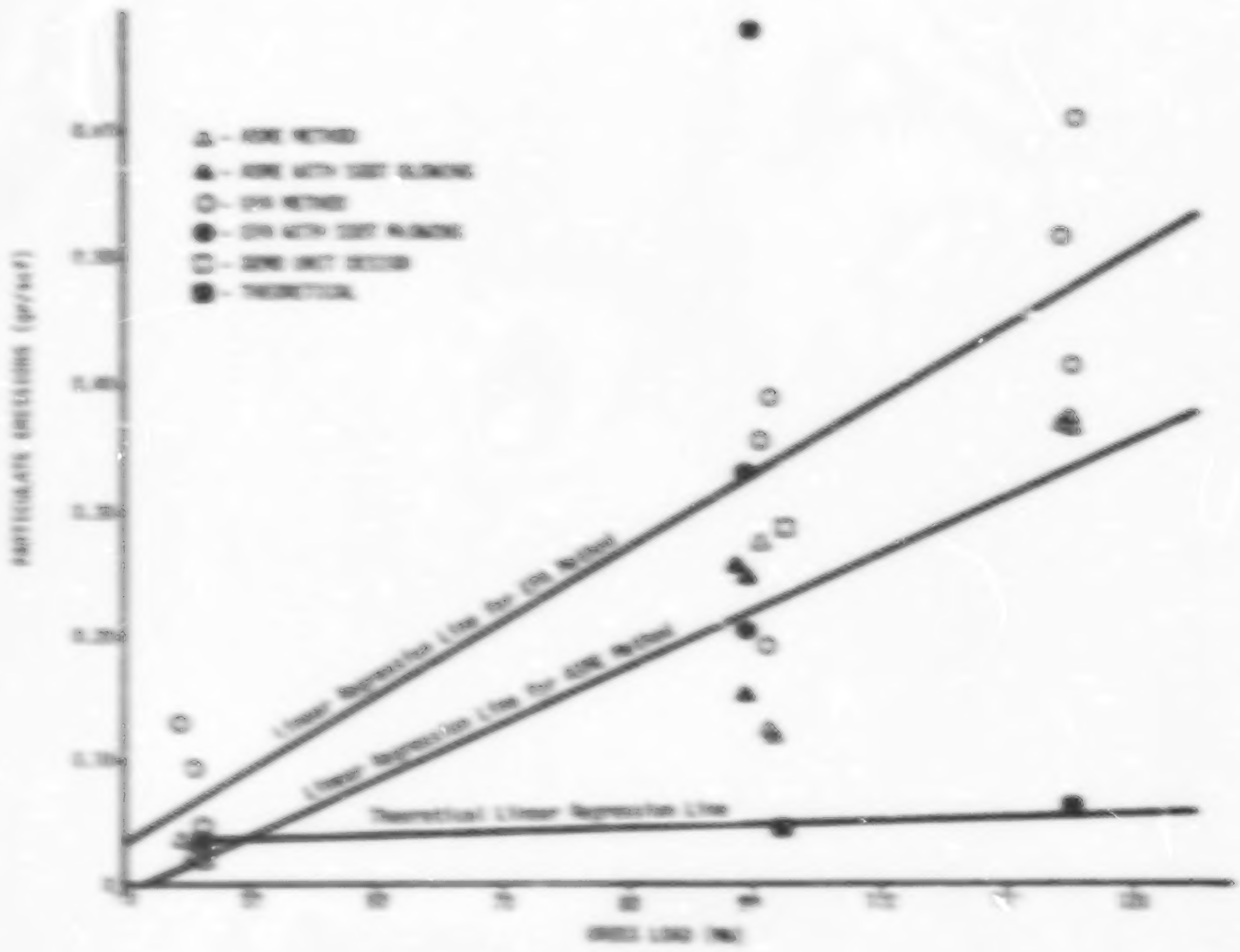


FIGURE 3-[illegible]
PARTICULATE EMISSIONS (GR/SCF) OUTLET [illegible] vs. GROSS LOAD
TEST SERIES 1 & 2



rates before the precipitator were higher than theoretical when operating at 80% load factor (92MW).

Outlet particulate emission rates by the method were higher than theoretical at 92MW and 115MW and about equal to theoretical at 66MW. ESP efficiency is discussed in 3.2.6.6. The poor collection efficiency resulted in particulate emissions higher than Demo. Unit design. At 92MW load, particulate emission rates averaged 708 lb/hr by the EPA method compared to Demo. Unit design values of 550 lb/hr. Measured grain loading was 0.24 gr/ACF vs. 0.20 gr/ACF design.

3.2.6.3 Comparison with the New Source Performance Standard

Relevant data are included in Table B-22.

All tests exceeded the Federal New Source Performance Standard of 0.10 lb/MMBTU maximum two-hour average. The emissions at loads of about 66MW were only slightly higher than the standard whereas the emissions at 92MW and 115MW were much higher than the standard.

3.2.6.4 Dependency on Load

Relevant data are included in Table B-22 and on Figures 3-17, 3-18 and 3-19.

Load dependency is illustrated on Figures 3-17, 3-18 and 3-19. Particulate emissions increased with load at inlet the air heater as expected. At the outlet the emissions were more dependent on load than would have occurred with the ESP performing at design efficiency.

3.2.6.5 Dependency on Other Boiler Control Settings

Relevant data are included in Table B-22 and on Figures 3-17 and 3-18.

Figure 3-17 shows that the mass emission rates inlet the air heaters were significantly higher with soot blowing than without soot blowing at 92MW. However, no effect from soot blowing is apparent after the precipitator.

No definite correlation with ash content of the coal can be discerned. Figure 3-17 indicates that measured values of particulate rates inlet the air heaters by the ASME method were substantially less than theoretical values at all loads.

Dependency on collector efficiency is discussed in the following subsection.

3.2.6.6 Collector Efficiency

Relevant data are included in Table B-22.

The dust collector efficiency varied from 89.3% to 98.9% and averaged 94.7% with normal operation of the boiler. The highest efficiencies were experienced at 46MW (96.5%) and the lowest efficiencies were experienced at 115MW (90.0% to 92.4%). Design efficiency is 98.5%. There was no apparent affect on the efficiency from soot blowing at 92MW. Operating performance of the collector is discussed in Section 3.4.

3.2.6.7 Particle Size

Relevant data are shown in Tables 3-8 and 3-9 and on Figures B-1 thru B-3.

Size distribution of the particulate matter was determined at the precipitator outlet location by an in-situ Brinks Cascade Impactor. The cascade impactor has the capability to separate particles into six different size categories, varying from greater than seven microns (μ) in diameter to less than 0.1μ. However, at the higher sampling rates required to insure adequate loading of the last stages, the minimum diameter of particles trapped in the first stage decreases to 3.5μ. On the average, 50% of the particulate mass was less than 3.0μ diameter. Tables 3-8 and 3-9 include the pulverized coal size for comparison.

The particle sizing results in some cases are biased by sample carry-over from the first stage of the sampler. The effect of this is to shift the mass median diameter results downward. In a few cases the carry-over was significant enough to invalidate the test results. For Test Series One, tests No. 16 and 17 were invalidated due to inadequate sample. The results of test No. 10 were affected by carry-over from the first stage of the sampler.

The overloading of the first stage of the impactor was due to having to collect a large enough sample to insure adequate loading on the last stages to weigh accurately. The heavy loading on the first stage is suggestive of a significant fraction of the particulate matter being larger than 5μ in diameter. The result is to insure a slight conservative bias error; that is, a bias error toward larger fractions of smaller size particles.

3.2.6.8 Potential Effects on Demo. Unit Performance

Particulate will be removed from the flue gas by an orifice contactor located ahead of the absorber. A removal efficiency of 70% is expected at particulate rates of 550 lb/hr. Higher than design inlet grain loadings might result in higher grain loadings in the gas to the absorber. Additionally, higher grain loadings will increase fly ash purge rates with a subsequent increase in purge water requirements. Increased grain loadings to the absorber will require more frequent washings of the fly ash filter. Also, there are potential effects on operation of the Demo. Unit from some of the trace metals present in the particulate matter. Particulate particle size could also affect the removal efficiency of the orifice contactor and result in higher grain loadings to the absorber. The grain loading and particle size measurements have been documented in the preceding subsection. Trace element emissions are reported in 3.2.7.

3.2.7 Trace Element Emissions

Relevant data re included in Table 3-15.

TABLE 3-15

RATIONALE FOR TRACE ELEMENT SELECTION

Antimony	Toxicity and concentration
Arsenic	Toxicity
Beryllium	Toxicity
Cadmium	Toxicity
Calcium	Potential process effect
Chlorine	Potential process effect
Chromium	Potential process effect
Copper	Potential oxidation catalyst
Fluorine	Pollutant
Iron	Potential oxidation catalyst
Lead	Toxicity and concentration
Magnesium	Potential process effect
Manganese	Potential oxidation catalyst
Mercury	Toxicity
Nickel	Toxicity
Selenium	Toxicity and concentration
Tin	Toxicity and concentration
Vanadium	Potential oxidation catalyst
Zinc	Toxicity

A group of 19 trace elements were selected for analysis. The selection was based on initial characterization testing (performed by TRW, July 6-13, 1973) to define concentrations, on a literature review, and on other TRW studies. The rationale for selection are indicated in Table 3-15.

3.2.7.1 Concentration Effects

Relevant data are included in Table 3-16.

Table 3-16 ranks the trace metals (those present as particulate in the flue gas) by concentration effect (C.E.). Concentration effect shows the degree of concentration of an element in the fly ash emissions over its concentration in ash in the coal. The ranking indicates that the higher the C.E. number the greater the tendency of the element to escape collection due to association with fine particulate and/or association with high resistivity particulate. Concentration effects greater than one were indicated for 10 out of 16 particulate species analyzed. Similar concentration effects were observed during off normal operating conditions (Test Series 2).

3.2.7.2 Concentrations in Flue Gas Particulate

Tables 3-17 and 3-18 show the concentrations of trace elements in the coal and in the fly ash at the precipitator outlet.

3.2.7.3 Emission of Halogens

Relevant data are included in Tables B-5, B-6, B-7, B-8, B-23, B-24, B-25, B-26, B-27 and B-28.

Fluoride and chloride concentrations were determined in the coal, collected fly ash, and the flue gas. Because of sampling constraints, the halogens in the emissions were determined only during Test Series 3 (Tests 22 and 23). The results are summarized as follows:

TABLE 3-16

TRACE METALS CONCENTRATION EFFECT
TEST SERIES I

	As Fired Coal$^{(1)}$	Flue Gas Particulate$^{(1)}$	C.E.$^{(2)}$
Se	8.38	850	101.43
Cd	4.15	65.5	15.78
As	5.75	77.8	13.53
Ni	135	452	3.35
Sn	33.80	88.0	2.60
V	186	415	2.23
Cr	474	971	2.05
Be	8.46	15.4	1.82
Cu	102	141	1.38
Pb	152	191	1.26
Zn	305	298	0.98
Ca	20800	17400	0.84
Fe	72900	58600	0.80
Sb	271	203	0.75
Mn	338	218	0.64
Mg	635	155	0.24

(1) $\frac{\text{lb trace element}}{\text{lb ash}} \times 10^6$

(2) Concentration Effect, ratio of element concentration in flue gas particulate to element concentration in coal ash.

TABLE 3-17
TRACE METALS CONCENTRATIONS IN COAL, PPM

	As Fired Coal(1) (Test Series 5)	As Fired Coal(1) (Test Series 1)
Fe	126914	72900
V	65778	186
Mn	35024	338
Ca	26906	20800
Ni	21995	136
Sn	10699	34
Mg	9121	635
Zn	316	306
Cr	138	474
Cu	118	102
Pb	110	152
Be	0.806	8.46
Sb	0.806	271
Se	0.806	8.38
As	0.396	5.76
Cd	0.073	4.16

(1) $\frac{\text{lb Trace Element}}{\text{lb Ash}} \times 10^6$

TABLE 3-18

TRACE METALS CONCENTRATIONS IN THE FLUE GAS, PPM

	Flue Gas Particulate[1] (Test Series 6)	Flue Gas Particulate[1] (Test Series 1)
Fe	225787	58600
Mg	10006	155
Ca	9149	17400
Zn	2180	298
Sn	587	88.0
Ni	352	452
Cr	179	971
Pb	176	191
Cu	160	141
Mn	131	218
Be	0.106	16.4
Sb	0.106	203
Se	0.106	337
V	0.106	416
As	0.052	77.8
Cd	0.011	65.5

---

[1] $\frac{\text{lb Trace Element}}{\text{lb Ash}} \times 10^6$

Test	22	23
F^- in Coal, ppm	125	116
F^- in Ash, ppm	143	134
F^- in Flue Gas, ppm w/w dry	7.0	9.9
F^- in Flue Gas, lb/hr	9.3	12.1
Cl^- in Coal, ppm	300	300
Flue Gas Total, Mlb/hr dry	1326	1223
Cl^- in Ash, ppm	Nil	303
Cl^- in Flue Gas, ppm w/w dry	9.2	13.2
Cl^- in Flue Gas, lb/hr	12.2	16.1

Fluorides and chloride were determined on the as fired coal and on the collected ash for the applicable tests during which 3% S coal was burned. Average concentrations in the coal were 95 ppm F^- and 300 ppm Cl^- for 17 tests. Chloride is reported only to the nearest 100 ppm. Average concentrations in the collected fly ash were 100 ppm F^- and less than 100 ppm Cl^- for 15 tests. No chloride was detected in the ash for eight of the tests. As a rough approximation, about 10% of the fluoride was removed with the collected fly ash. A corresponding approximation of chloride removal was not possible because of the large number of tests showing no chloride in the ash.

3.2.7.4 Emission of H_2S, Mercury

Hydrogen sulfide and mercury emissions were determined during Test Series 3. Less than the minimum detectable quantity of H_2S was being emitted, i.e., less than 0.3 lb/hr (0.19 ppmv). Indicated presence of mercury was also less than the minimum detectable quantity, or less than 0.001 lb/hr (0.001 ppmv).

3.2.7.5 Carbon Monoxide and Hydrocarbons

Carbon monoxide and total hydrocarbons were monitored continuously during Test Series 3. Ambient air inleakage into the sampling system aborted these tests. Carbon monoxide and hydrocarbons will be monitored continuously during the Demonstration.

3.3 FLUE GAS CHARACTERIZATION - OFF NORMAL OPERATION

This section describes the results of the characterization of outlet flue gas at operating conditions other than normal (Test Series 2). Outlet flue gas volume, physical characteristics, emission concentrations and rates of SOx, NOx and particulate matter as well as other flue gas constituents were measured and the data evaluated.

3.3.1 Scope of Characterization

Testing was performed in triplicate at approximately 100% load (118MW), with 3.2% S coal and without soot blowing to examine the following effects:

- High grain loading (test no's. 11-13) - to simulate effect of other boilers on Demo. Unit performance
- Excess of combustion air (test no's. 14, 15, 18) - to maximize NOx formation
- Excess of air inleakage (test no's. 19-21) - to maximize flue gas volume

Twelve additional tests were performed using a low sulfur coal. The results are discussed in Section 3.6. The purposes of the characterizations are those described in 3.2.1.

3.3.2 Flue Gas Profile

Relevant data are summarized in Table B-29.

Table B-29 is a summary of the flue gas characterization data for Test Series 2 during which grain loading, combustion air and air inleakage were increased. This data provides documentation of the baseline flue gas profile for later comparison with the results for determining the effects of the stated off normal conditions on Demo. Unit performance.

3.3.3 High Grain Loading

Relevant data are included in Table B-29 and B-30.

In order to simulate the effect of other boilers on Demo. Unit performance, the last of three ESP fields was not energized. All tests were at 100% load. At this operating condition, the design dust collection efficiency drops from 98.5% to 95.6%. Measured collection efficiencies were as follows:

Test 11	81.6%
Test 12	82.0%
Test 13	82.1%

Average efficiency with all three fields in operation was 96.2%.

Particulate emissions averaged 1843 lb/hr compared to an average of 807 lb/hr at full load with all three fields in operation. Grain loading was 0.52 gr/ACF with two fields versus 0.25 gr/ACF with three fields. Within the limits of the test procedure, there was no apparent difference in the particle size distribution between two field and three field operation. Stage to stage carryover was indicated during tests 12 and 13 but not enough to invalidate the tests (see 3.2.6.7).

3.3.4 Excess Combustion Air

Relevant data are included in Table B-29.

An excess of air above normal was added to the combustion zone to attempt to change the NOx concentration relative to SO_2. The purpose was to provide another level of NOx concentration relative to SO_2 concentration and to examine its effect on Demo. Unit performance. The Baseline results are reported in 3.2.5.3. The relative NOx concentration decreased at the higher level of excess combustion air whereas just the reverse was expected.

3.3.5 Excess Flue Gas Volume

Relevant data are included in Table B-29 and B-31.

An excess of inleakage air was added by opening access doors at the air heater outlets at full load. During the first test of the three replicate test set, the doors were only partially opened with only a minimum increase in flue gas rate resulting. The doors were wide open during the other two tests and about a 15% increase over normal operation of flue gas volume occurred. Affect on the more important flue gas parameters are summarized as follows:

	Normal Volume	Excess Volume
Volume, Macfm	403	468
Mass Rate, Mlb/Hr.	1273	1510
SO_2, ppm	2764	2247
Particulate, gr/ACF	0.26	0.10
Excess Air, %	34	57

3.4 PRECIPITATOR PERFORMANCE

3.4.1 Scope(8)

Relevant data are shown in Table 3-19.

The flue gas from Mitchell No. 11 is removed by a cold end electrostatic precipitator (ESP) manufactured by American Standard Company. The specifications for this ESP are listed in Table 3-19. The measured ESP efficiencies were discussed in 3.2.6.6 and 3.3.3. In the discussion to follow, the performance of the ESP as it affects the particulate removal efficiency is assessed. The parameters selected for indicating effects on performance are specific corona power and migration velocity. The specific corona power may be expressed either as watts per gas flow rate or as watts per collector plate area. A loss in efficiency results from an inability to maintain design specific power levels. Possible causes are:

- High dust resistivity
- Dust accumulation on the electrodes
- Unusually fine particle size
- Improper rectifier and control operation
- Internal failures such as broken wires, insulator failure, dust accumulation above hopper levels

The other critical parameter is the migration velocity w, a rate constant describing the particle velocity component in the direction of the collection electrode. Its effect on efficiency is expressed in the Deutsch-Anderson equation(9) as follows:

$$\text{Eff.} = 1 - \exp\left(-\frac{A}{V_g} w\right)$$

where,

Eff. = collection efficiency

A = electrode area

V_g = rate of gas flow

w = particle migration velocity

TABLE 3-19

PRECIPITATOR SPECIFICATIONS

Design CFM	410,000
T, °F	290
Inlet, gr/SCFD	3.5 to 4.5
ΔP, "H_2O	0.4
Removal, %	98.5
Rate Constant, Ft./Sec.	0.5
Plates, $Ft.^2$	58,240
Treatment Length, Ft.	17.3
# Fields	3
# Ducts	56 (09")
Wire Ft.	40,320 (07")
Wire Rating, ma./Ft.	0.08
Treatment Time, Sec.	3.2
Delivery	July 1969
# Plate Rappers	32
# Wire Vibrators	12
Hopper Ash Capacity Minimum	8 hrs.
# Bus Sections	6
Plate Height, Ft.	30
Energization	Half Wave
Rating KV	70
Rating ma.	1800, 800, 600

Provision in the unit for another field, 6' treatment length above hopper #2, can be addud later

Expected removal w/field #1 only 87.7%

Expected removal w/fields #1 - 2 only 95.6%

Expected hopper #3 collects 2.8% of the dust

Ash removal pneumatically by 3 lines (fields 1, 2, 3)

No. ash hoppers - 12

The migration velocity varies with resistivity, particle size, gas velocity distribution, reentrainment losses and other factors. It is being determined experimentally by inserting efficiencies and gas flow into the Deutsch-Anderson equation.

To evaluate performance, the efficiencies are correlated with specific corona power to assess the power level effects. The efficiencies are then used to calculate migration velocity which will be correlated with such variables as specific corona power and sulfur content of the flue gas. Particle size distribution and resistivity are not known.

3.4.2 Operating Performance

Relevant data are included in Tables B-32 and B-33 and on Figures 3-20 and 3-21.

Figure 3-20 indicates some increase in efficiency with specific corona power, although the data are widely scattered. Figure 3-21 is a plot of migration velocity vs. the concentration of SO_3 in the flue gas. No correlation can be discerned within the limits of SO_3 concentrations observed. Also, there appears to be no correlation of migration velocity with specific corona power.

FIGURE 3.20
Collector Efficiency (%) vs. Useful Corona Power (watts/1000 cfm)
Test Series 1, 2 & 3

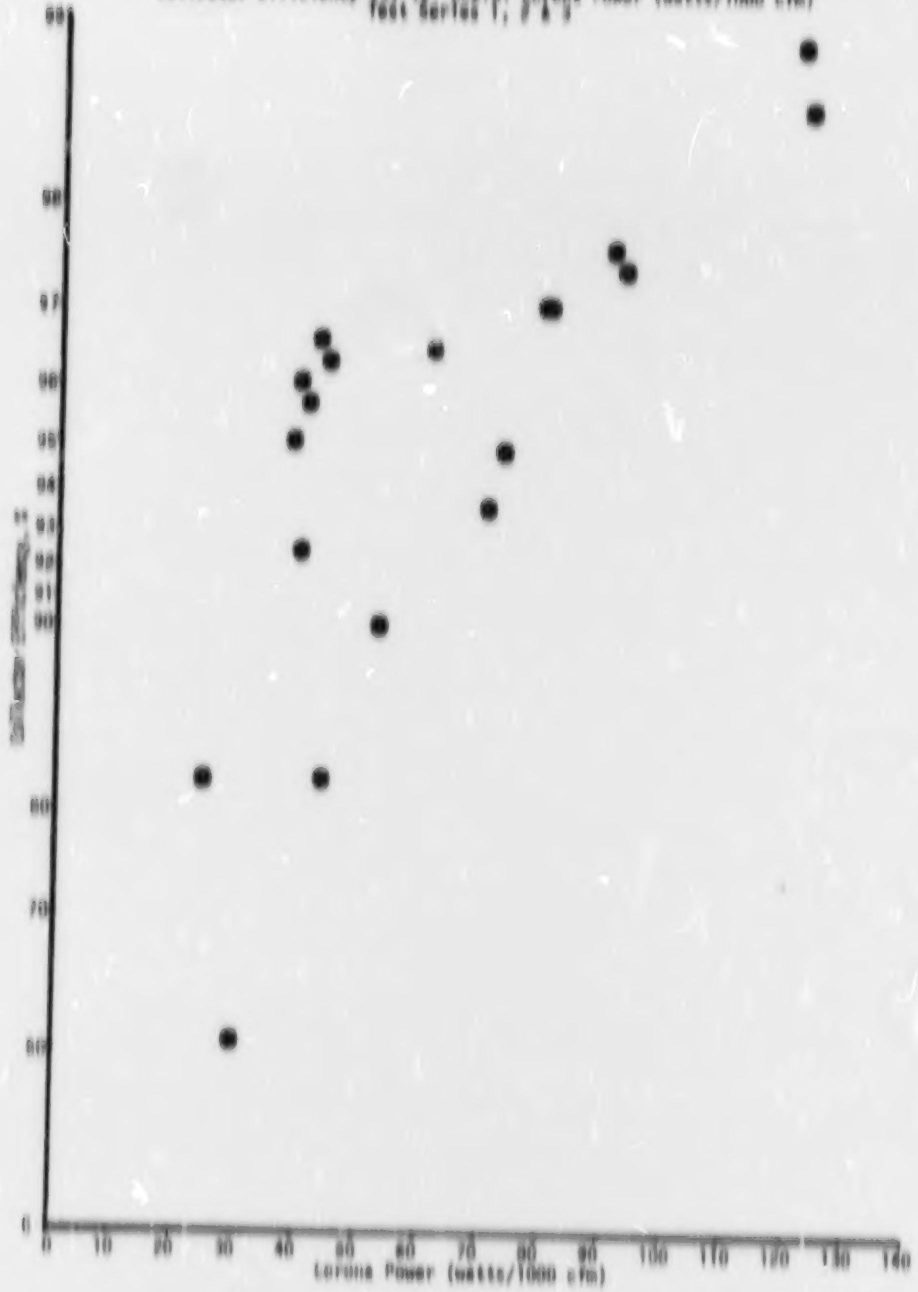
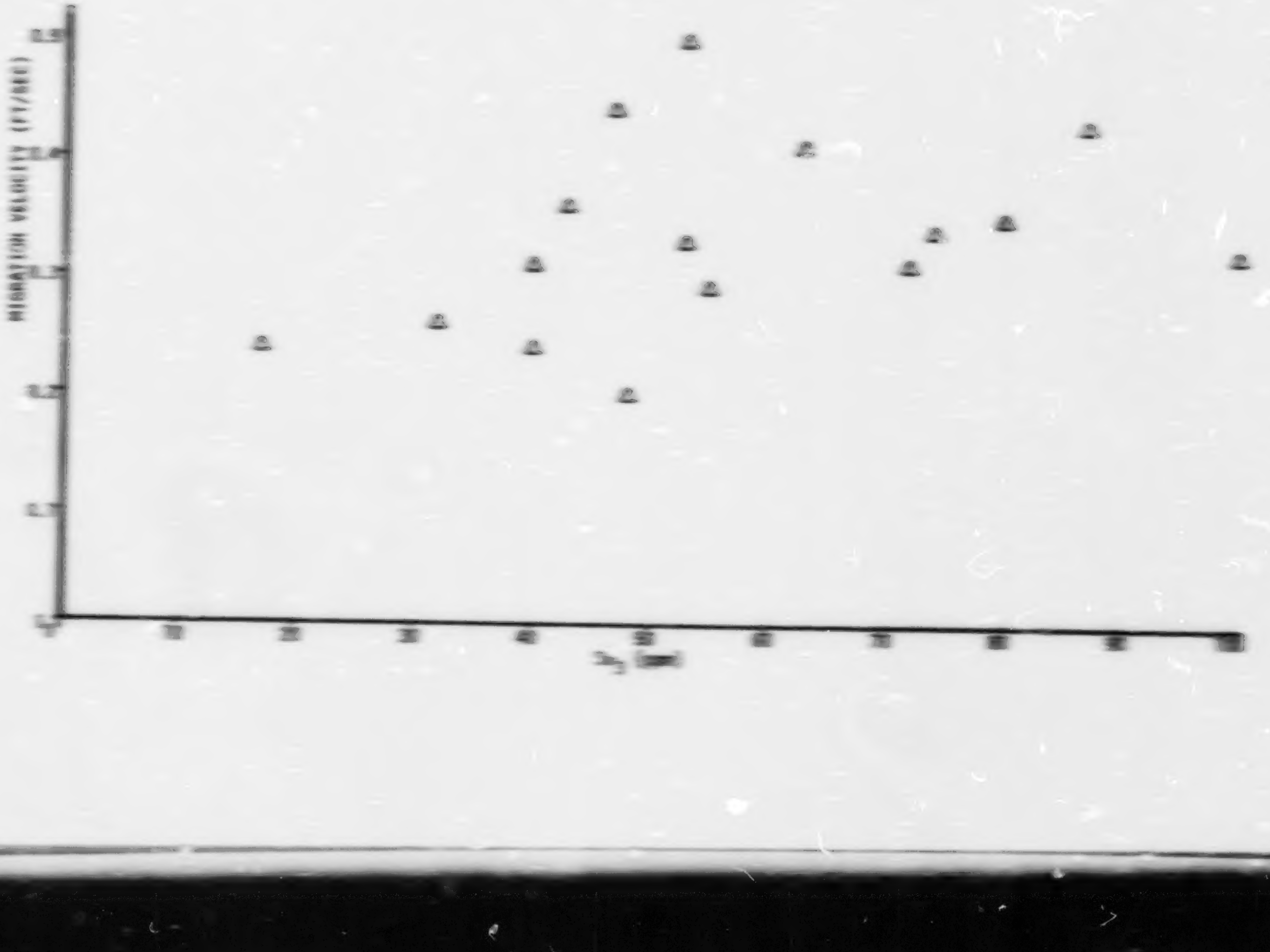


FIGURE 3-21
MIGRATION VELOCITY vs. SO2 CONCENTRATION
TEST SERIES 1, 2, & 3



3.5 CYCLICAL AND TREND EFFECTS

3.5.1 Scope

Relevant data are included in Tables 3-20 and 3-21.

A limited number of parameters were selected for displaying trends or cycles in the measurements. Selection was of those parameters which:

- Are expected to impact boiler operating performance and emission levels (fuel characteristics).
- Show the thermal efficiency (heat rate).
- Show performance of air heaters.
- Show performance of ESP.

Boiler age and maintenance history are also important trend effects. Sixty percent of the tests were performed during May 1974 and the remaining tests were performed during April and May 1975. This gap of nearly a full year in the field testing allows the examination of the data for long term effects due to boiler age and maintenance history. Tables 3-20 and 3-21 present the date and time of testing and the operating conditions specified for testing. The parameters examined for cyclical and trend effects are as follows:

- Coal parameters -
  - HHV, dry, ash free basis
  - S, dry, ash free basis
  - C, dry, ash free basis
  - H, dry, ash free basis
  - O, dry, ash free basis
  - Ash, dry basis
  - H_2O
- Air temperature -
  - air humidity, lb/lb dry air
- Heat rate

TABLE 3-21
FIELD TEST SCHEDULE
Normal Fuel (3% Sulfur)

Test No.	Date	Start Time, Hours	Load, Gross (MW)	Soot Blowing Status	Coal Sulfur, %	Off Normal Condition
1	5/15/74	1142	46	Off	3	None
2	5/17/75	0902	92	Off	3	None
3	5/17/74	1500	92	On	3	None
4	5/19/74	0847	92	Off	3	None
5	5/19/74	1347	92	On	3	None
6	5/20/74	0846	92	Off	3	None
7	5/20/74	1322	92	On	3	None
8	5/22/74	1333	115	Off	3	None
9	5/22/74	1900	115	Off	3	None
10	5/23/74	0955	115	Off	3	None
11	5/23/74	1500	115	Off	3	Ash
12	5/24/74	0855	115	Off	3	Ash
13	5/24/74	1420	115	Off	3	Ash
14	5/25/74	0823	115	Off	3	ESA
15	5/25/74	1415	115	Off	3	ESA
16	5/26/75	0850	46	Off	3	None
17	5/26/74	1340	46	Off	3	None
18	5/27/74	0850	115	Off	3	ESA
19	5/27/74	1530	115	Off	3	XOL
20	5/29/74	0940	115	Off	3	XOL
21	5/29/74	1500	115	Off	3	XOL
22	4/17/75	1540	115	Off	3	None
23	4/18/75	1308	115	Off	3	None

ASH - High grain loading; ESA - Excess combustion air; XOL - Excess air inleakage

TABLE 3-21
FIELD TEST SCHEDULE
Low Sulfur Fuel (1% Sulfur)

Test No.	Date	Start Time, Hours	Load, Gross (MW)	Soot Blowing Status	Coal Sulfur, %	Off Normal Condition
24	4/25/75	0945	111	OFF	1	None
25	4/25/75	1500	111	OFF	1	None
26	4/26/75	0930	46	OFF	1	None
27	4/26/75	1500	46	OFF	1	None
28	4/28/75	0915	92	OFF	1	None
29	4/28/75	1405	92	On	1	None
30	4/29/75	0900	92	OFF	1	None
31	4/29/75	1345	92	On	1	None
32	4/30/75	0945	92	OFF	1	None
33	5/01/75	0945	111	OFF	1	None
34	5/01/75	1430	92	On	1	None
35	5/02/75	0835	111	OFF	1	None

- Air Heater Temperatures -
  - gas out ID fan
  - gas out APH
  - gas in APH
  - air out APH
- ESP Specific Power, Overall

Tests 1-23 were run during operation with normal fuel (3% S). Tests 24-35 were run during operation with low sulfur fuel (1% S). Short term trends, if any, are indicated by plotting 6-point running averages. A limited assessment of long term trends was possible by comparing 1974 and 1975 data.

3.5.2 Fuel Characteristics

Relevant data are shown in Figures 3-22, 3-23, 3-24, 3-25, 3-26, 3-27 and 3-28.

Trend and cycle history is shown on the indicated figures. With the exception of ash and water content, the composition parameters for the coal are presented on a dry, ash free basis. Significant observations are as follows:

a. Heating value was stable with time. The low sulfur coal showed the highest cyclical variations.

b. Sulfur in the high sulfur coal was stable with time. One high value for sulfur in the low sulfur coal (Test 27) suggests contamination with a higher sulfur coal.

c. A slight upward trend in the carbon content of the high sulfur coal was indicated. Also, Tests 22 and 23, performed one year later than the other tests, were significantly higher in carbon content. The low sulfur coal showed the highest cyclical variations.

d. Hydrogen was stable with time except for lower concentrations during Tests 22 and 23.

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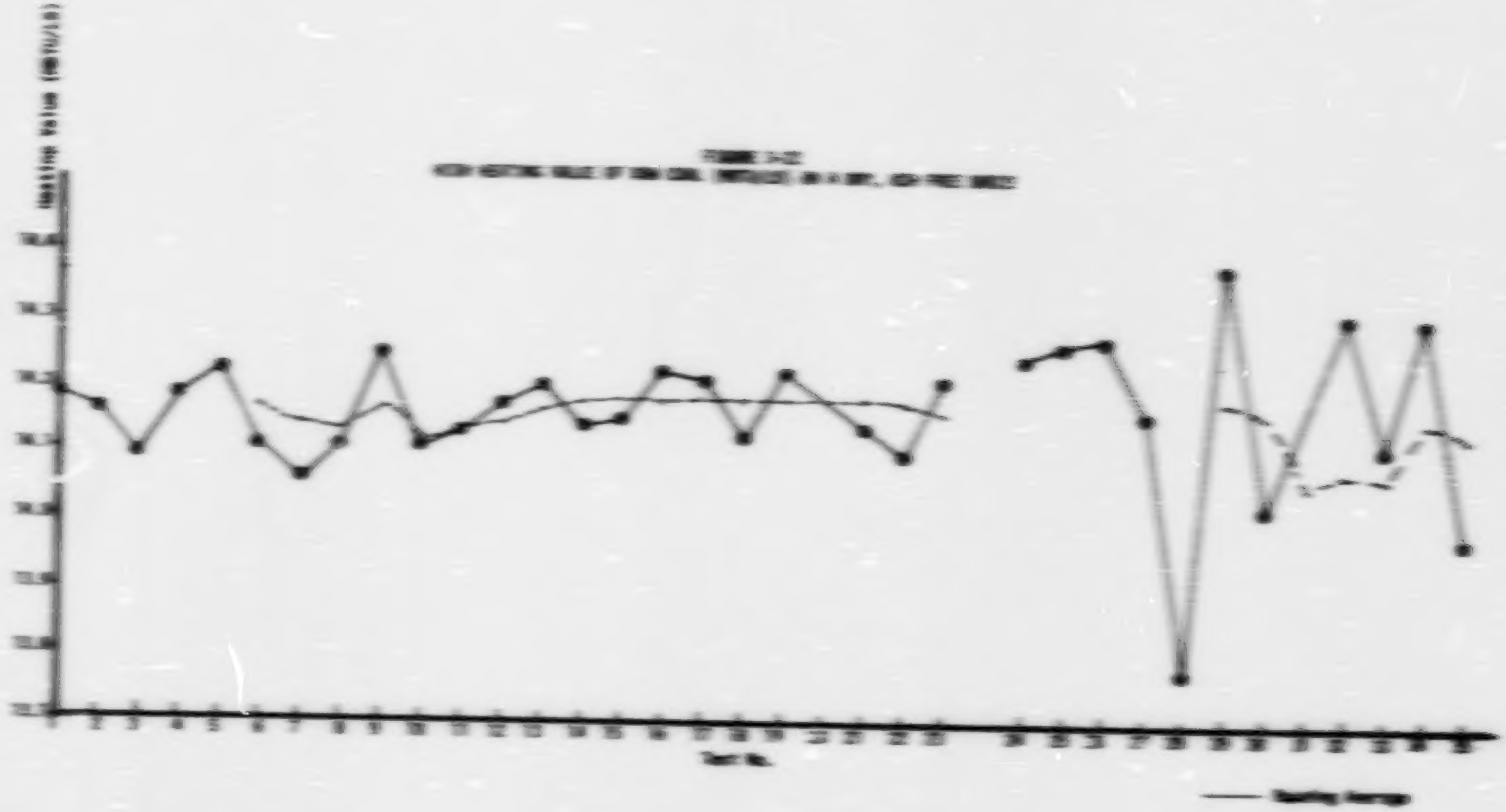
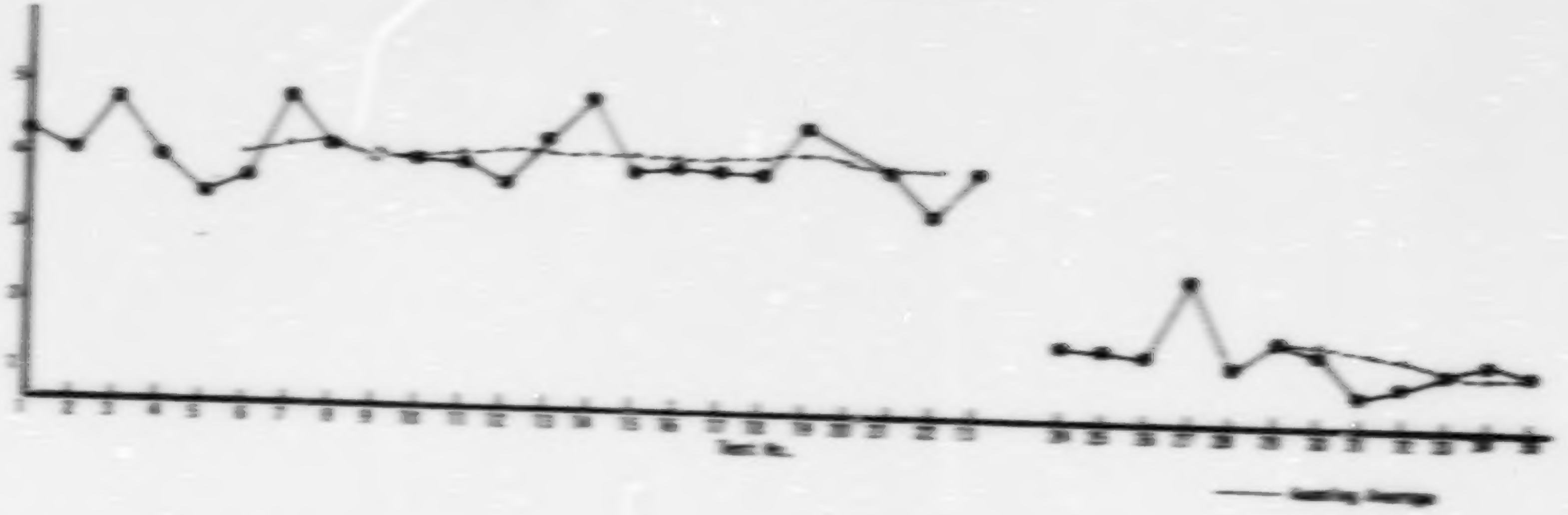

Heating Value (MBTU/lb)
Test No.
Running Average

FIGURE 3-23

WEIGHT PERCENT SULFUR IN RAW COAL ON A DRY, ASH-FREE BASIS



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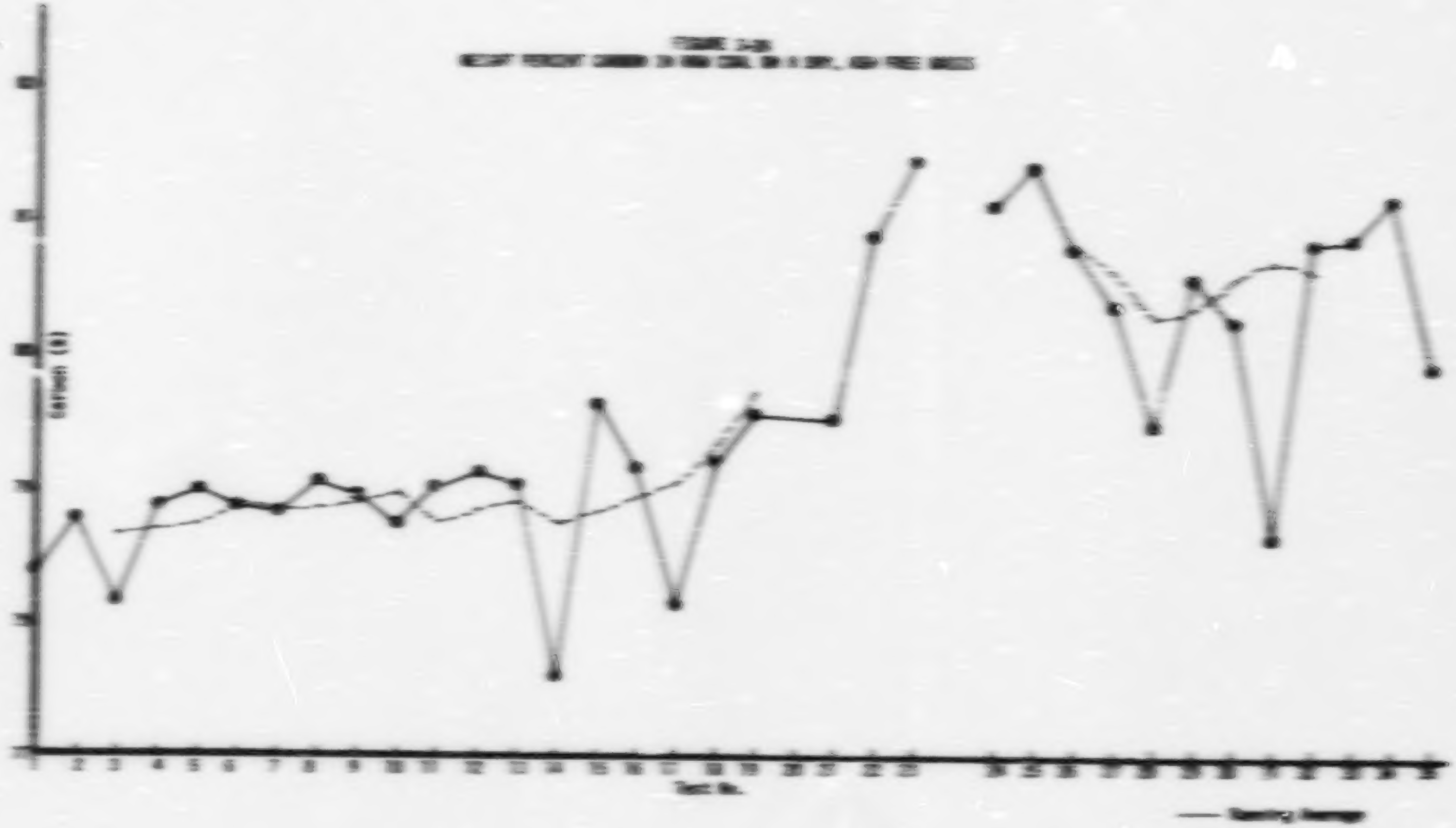
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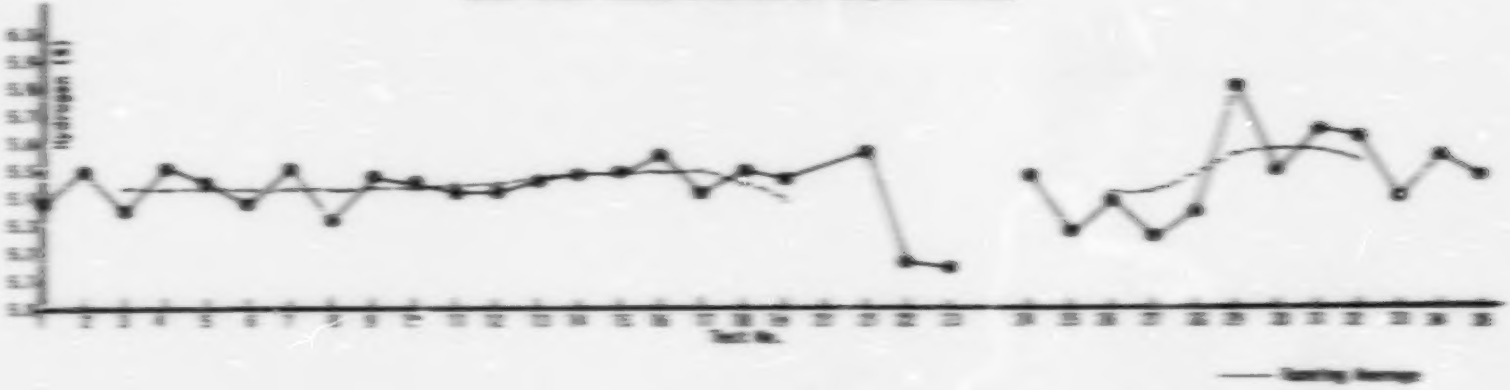
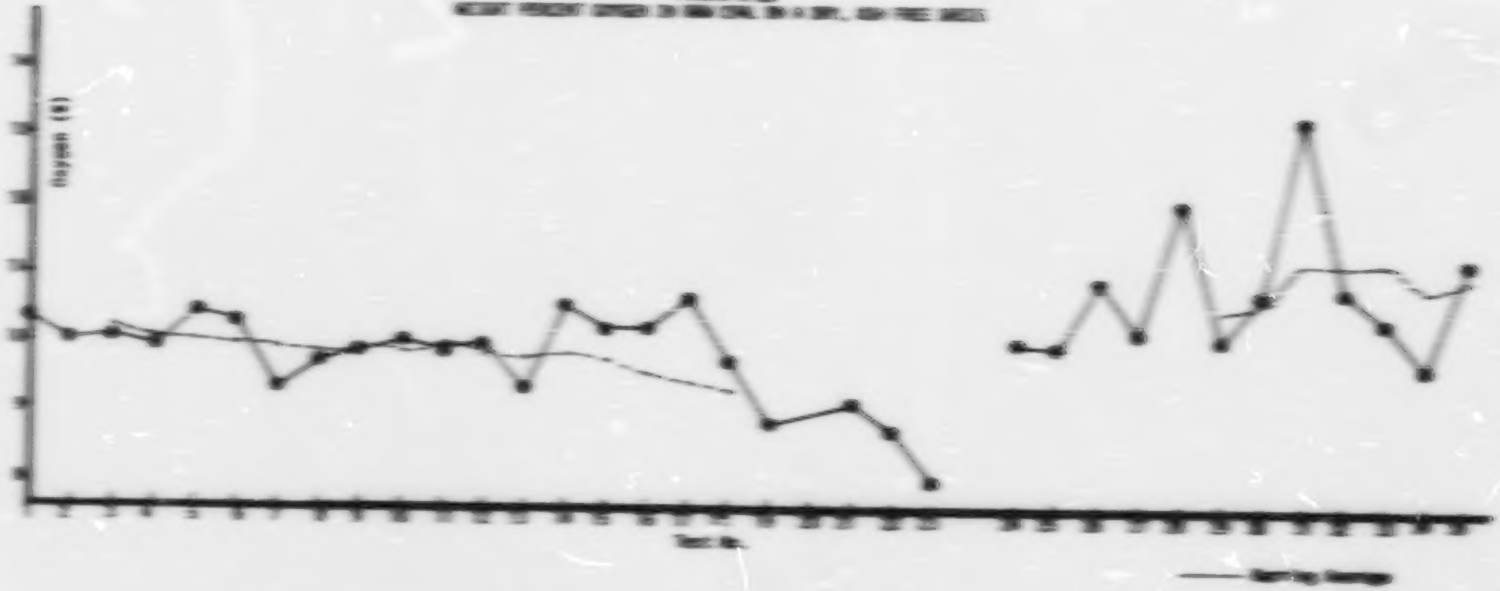
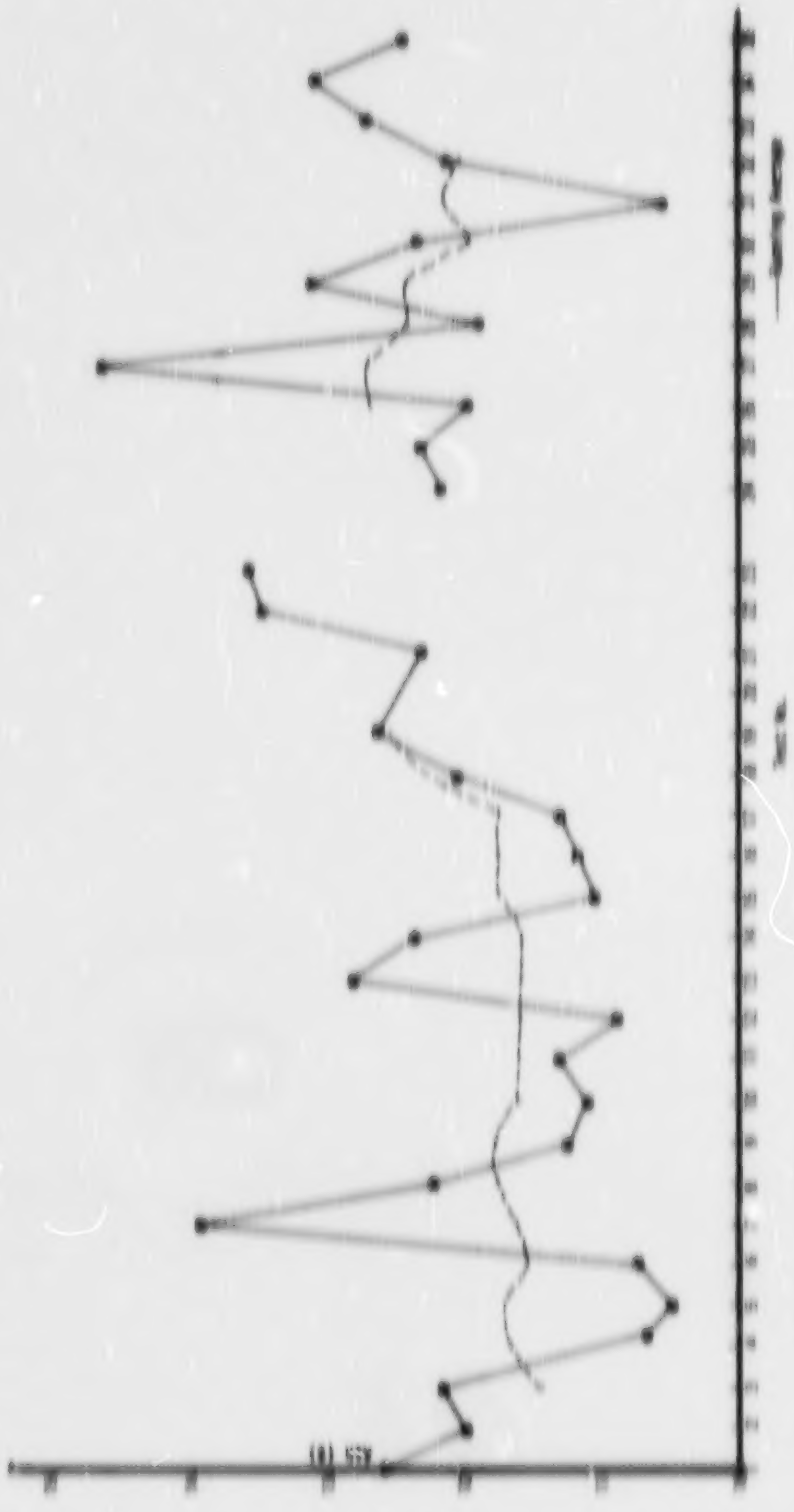

Hydrogen (%)
Test No.
Running Average

FIGURE 3-[illegible]
WEIGHT PERCENT OXYGEN IN RAW COAL ON A DRY, ASH FREE BASIS





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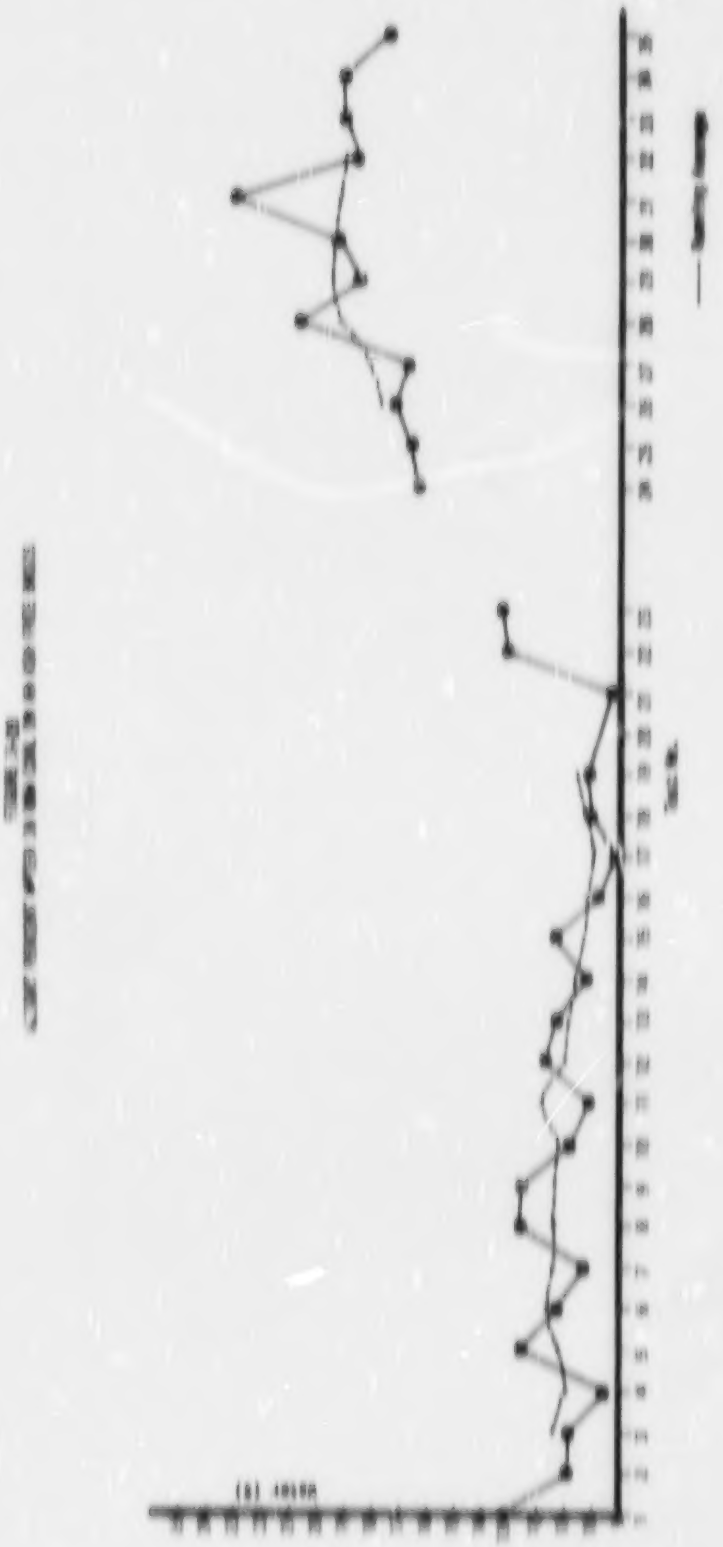


e. A slight downward trend in the oxygen content of the high sulfur coal was indicated (Tests 17 thru 23). Oxygen values for Tests 22 and 23 were lower than for the other high sulfur tests. Oxygen in the low sulfur coal was higher than in the high sulfur coal and also showed the highest cyclical variation. Oxygen in coal is determined by difference and the downward trend may indicate a dependence on the upward trend of the carbon content.

f. Ash in the high sulfur coal was stable with time except for higher ash contents during Tests 22 and 23. Ash in the low sulfur coal was slightly higher than in the high sulfur coal.

g. Moisture in the high sulfur coal showed a slight downward trend but increased during Tests 22 and 23. Moisture in the low sulfur coal was significantly higher.

It was pointed out in earlier discussions that scatter of the high sulfur coal component data was minor. Thus, the indicated trends and cycling have probably had minimum impact.

3.5.3 Heat Rates

Relevant data are shown on Figure 3-29.

The cycling is due primarily to load effects. Because of the dependence on load, no trend analysis was attempted.

3.5.4 Air Heater Performance

Figure 3-30 includes the trend lines for inlet and outlet air preheater temperatures as well as the stack temperature (outlet ID fan). Of interest is the outlet air temperature approach to inlet flue gas temperatures and the overall ΔT of the flue gas across the air heaters. There was no apparent long term trend over the one year period encompassing the field tests. The air heaters were washed just prior to start of the field tests in May 1974.

[illegible]

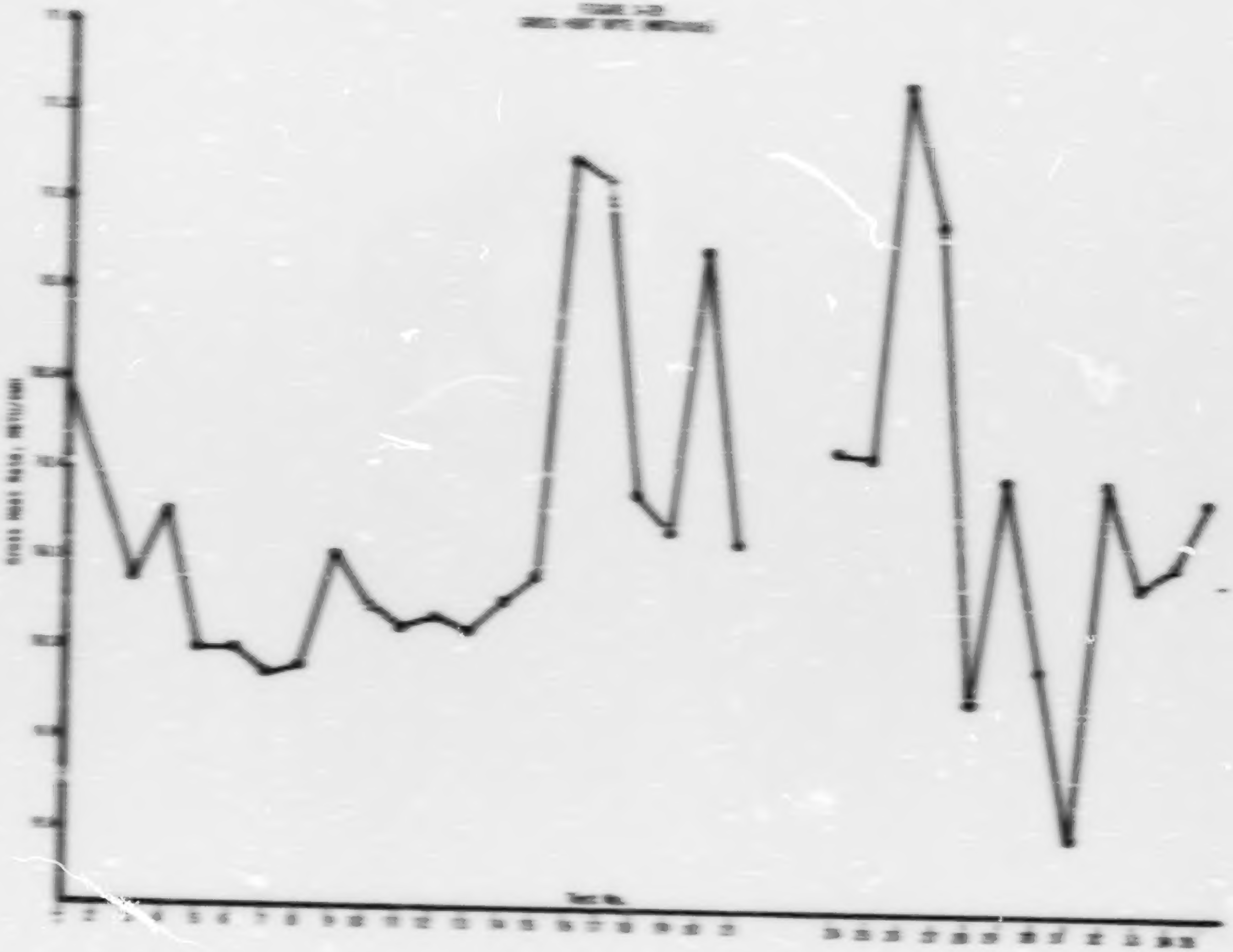
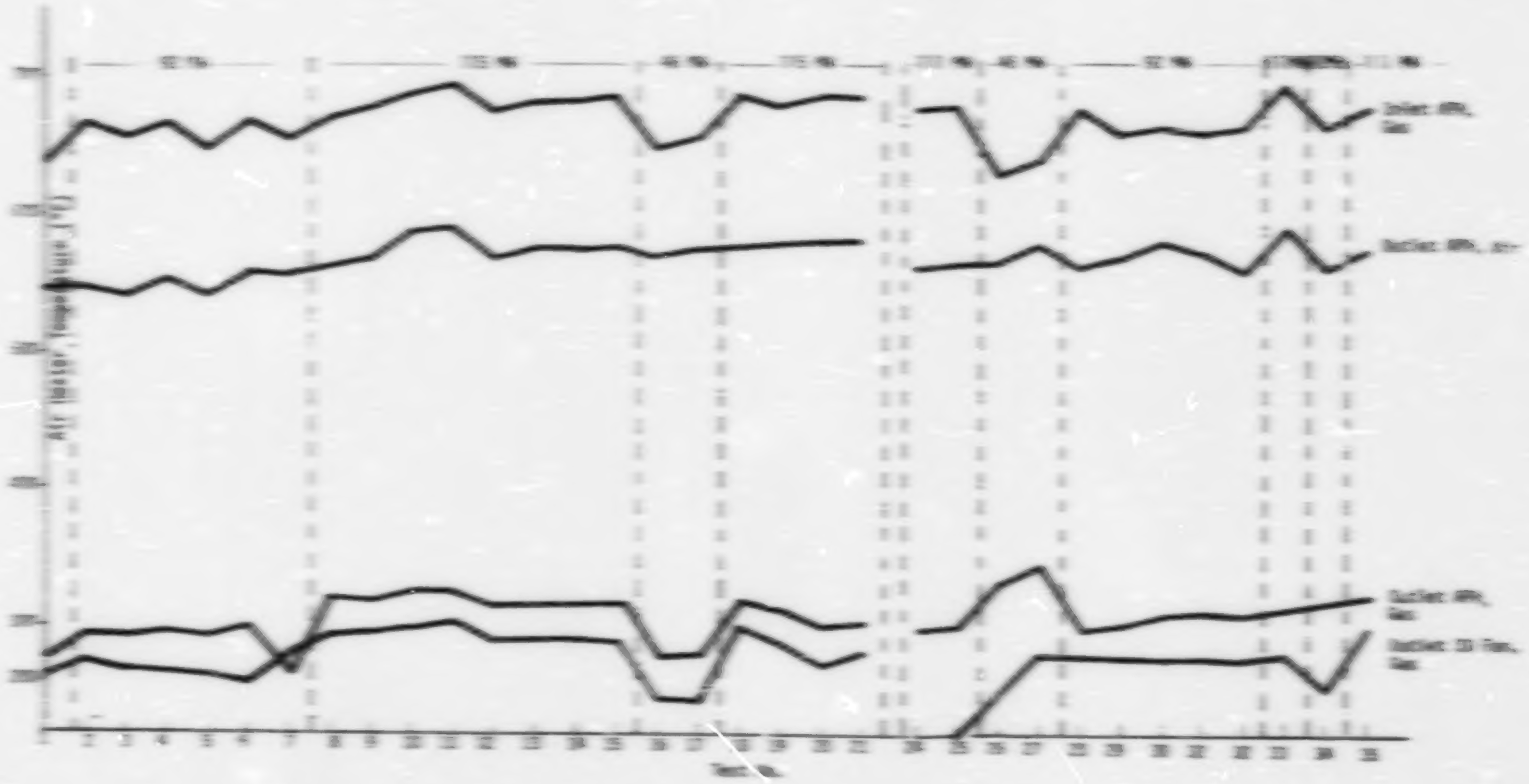

Test No.

FIGURE 3-38
AIR HEATER TEMPERATURES (°F)



3.5.5 Precipitator Performance

Trend and cyclical plots of useful corona power in watts per 1000 cfm of flue gas are shown on Figure 3-31. Significant observations are as follows:

a. An upward trend during the high sulfur tests reflects increased specific power requirements during the 46MW tests and during the high excess air and high air inleakage tests. Power was reduced during Tests 11, 12 and 13 due to operation with only two fields.

b. Somewhat more specific power was consumed during the low sulfur tests. Again, higher power use reflects operation at 46MW (Tests 26 and 27).

3.5.6 Ambient Conditions

Figure 3-32 includes the trend and cyclical plots of the humidity and temperature of the inlet air during testing. Significant observations are as follows:

a. Air temperature varied from 53°F to 79°F during the high sulfur tests. No definite upward trend was indicated during a test period extending through most of the month of May.

b. Humidity varied from 0.0045 lb/lb dry air to 0.0135 lb/lb dry air during the high sulfur tests. No trend was indicated.

c. Temperature varied from 48°F to 69°F during the low sulfur tests. An upward trend occurred during the test period extending from April 25 to May 2.

d. Humidity varied from 0.0045 lb/lb dry air to 0.0088 lb/lb dry air during the low sulfur tests. A slight upward trend was indicated.

FIGURE 3-31

USEFUL CORONA POWER (WATTS/1000 CFM)

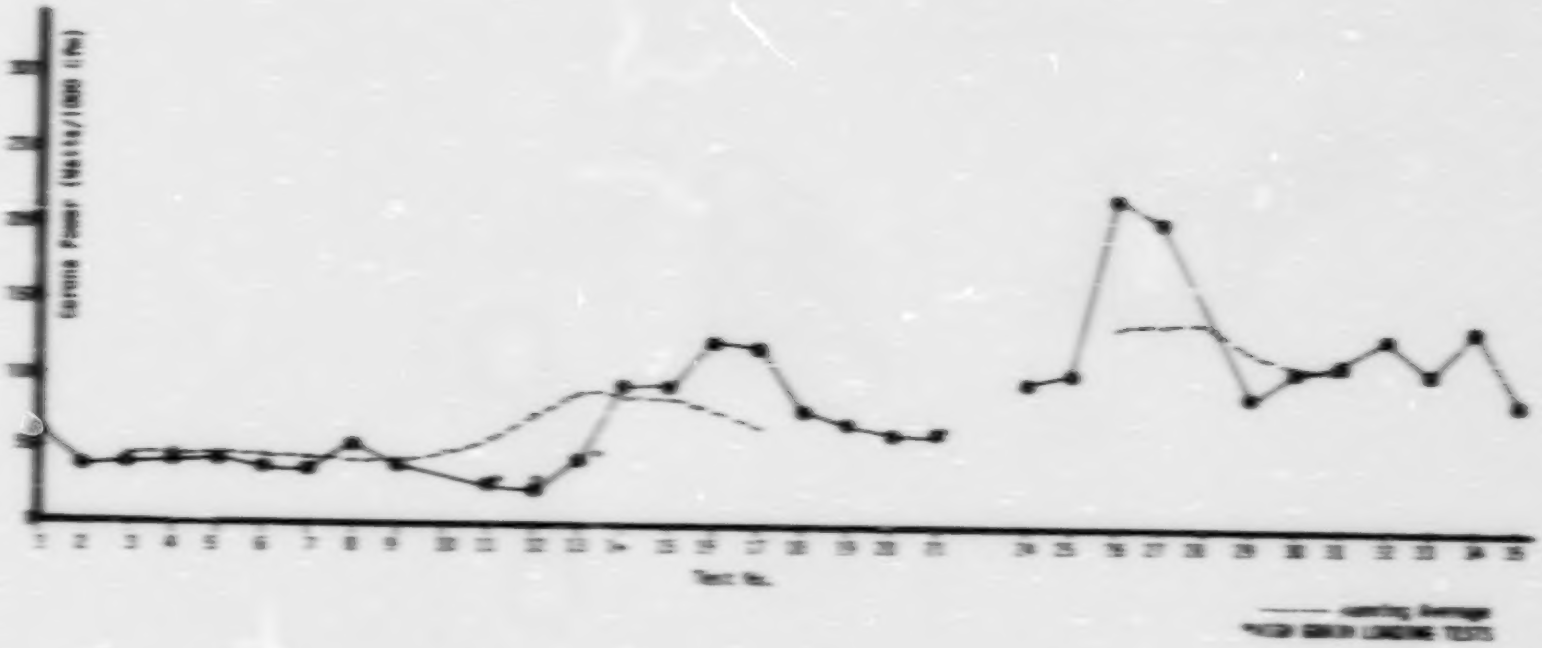
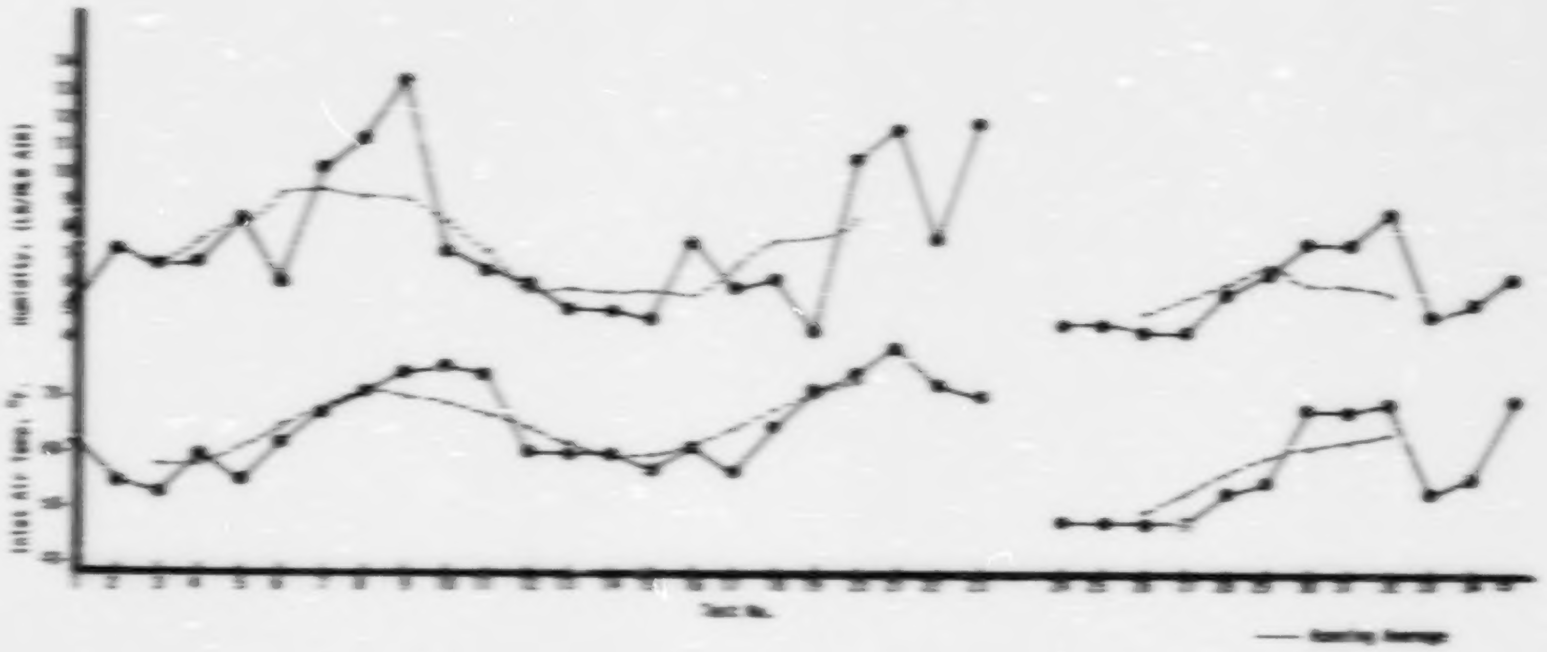


FIGURE 3-32
INLET AIR TEMPERATURE (°F)
HUMIDITY (LB/MLB AIR)



3.6 FLUE GAS CHARACTERIZATION - LOW SULFUR COAL

This section describes the results of a comprehensive test program for characterizing the outlet flue gas when a low sulfur coal is burned. The sulfur in the coal varied from 0.7% to 1.8% for this test series (Test Series 5). The purpose was to establish a baseline profile of the flue gas with the same low sulfur coal which will be burned while conducting special tests during the Demonstration. The special tests to be conducted during the Demonstration are to establish the operating performance of the Demo. Unit when treating gas with low inlet concentrations of SO_2.

3.6.1 Scope of Characterization

All operating conditions were normal with the exception of the coal burned. Test Series One (normal operation) was repeated so that data was collected at three levels of load plus an additional test set with soot blowing at one level of load (80% load factor).

The remainder of section 3.6 is devoted to a summary of the flue gas characterization results and their comparison with results when 3% S coal was burned. The results are presented as follows:

- A detailed physical-chemical profile is presented and summarized. The detailed data base is included in Appendix B.
- Measured flue gas parameters are compared with the corresponding Demo. Unit design parameters.
- Flue gas conditions having a potential effect on Demo. Unit performance are discussed.
- Baseline emission levels are documented.

3.6.2 Flue Gas Profile

Relevant data are included in Tables 3-22 and B-34, and in Figures B-10, B-11, B-12 and B-13.

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Table 3-22 is a summary of the flue gas characterization data. This data provides the documentation of pre-retrofit (baseline) flue gas conditions. It also will be referenced when evaluating the flue gas characterization data in the succeeding subsections. The data has been examined to determine which observations are outliers (invalid measurements). The outliers are not used in the correlations but the outlying observations are included in the tabulations. Examples of outliers are as follows:

Flue gas volume and mass rates - Test 29

Concentration and mass rates
of SO_2 in the flue gas - Test 27

Concentrations and mass rates
of SO_3 in the flue gas - Tests 24, 27, 28, 35

3.6.3 Volume, Temperature, Pressure

Relevant data are included in Tables 3-22 and B-35.

Flue gas volume varied from 183,000 acfm to 438,000 acfm over a load range of 44MW to 111.5MW. Average flue gas rates at an average load of about 92MW compared with normal operation and with Demo. Unit design were as follows:

	1% Sulfur	2% Sulfur	Design
Average Load, MW	87.9	90.0	92
Mass Rates, MMlb/hr.	1.09	1.10	1.02
Volume, acfm	346,000	336,000	320,000

Outlet duct temperatures as a function of the nominal gross load were as follows, in °F:

	1% Sulfur	3% Sulfur
46MW	262	250
92MW	269	268
115MW	303	296

Static pressures are tabulated in Table B-35.

3.6.4 Sulfur Oxides Emission Levels

Relevant data are included in Table B-36.

3.6.4.1 Comparison with Design

The data of Test 27 was not included in the analysis because of an apparent contamination of the coal by a higher sulfur content coal. Measured rates for comparison with the New Source Performance Standard average 1.9 lbs SO_2/MMBTU. The standard is 1.2 lb SO_2/MMBTU heat input and the difference is about what was expected for the coal sulfur content of these tests (1.1% average). The parameters critical to Demo. Unit performance compared with normal operation and Demo. Unit design were as follows:

	1% Sulfur	3% Sulfur	Design
Average Load, MW	87.9	90.0	92
SO_2 in flue gas (ppmv)	678	2493	2185
SO_2 in flue gas (lb/hr)	1605	5670	4842
SO_3 in flue gas (ppmv)	62	62	38
SO_3 in flue gas (lb/hr)	96	156	97

The data from Tests 24, 27, 28, and 35 were not used for averaging the SO_3 rates and concentrations.

3.6.4.2 Potential Effects on Demo. Unit Performance

A reduced equilibrium driving force, due to the lower concentrations of SO_2 may affect absorber performance. Also, sulfate purge rates are dependent on SO_3 levels in the inlet flue gas. However, the major effects are expected to be reduced evaporator load and reduced SO_2 rates to the reduction area. The concentration of SO_2 during the low sulfur tests was only 31% of the design value at 92MW. The ratios of SO_3 to SO_2 as a function of nominal gross load were as follows:

	SO_3/SO_2	
Load	1% Sulfur	3% Sulfur
46MW	0.028	0.033
92MW	0.056	0.022
115MW	0.027	0.025

The SO_3/SO_2 ratios were not much different from those at normal sulfur levels except for the 92MW tests. At 92MW, mass rates of SO_3 averaged 92 lb/hr with low sulfur coal compared to 155 lb/hr at the normal sulfur level in the fuel. Thus, sulfate purge levels as affected by SO_3 should be less than at normal operation.

3.6.5 NOx Emission Levels

Relevant data are included in Table 3-22.

3.6.5.1 Comparison with Design

Measured rates for comparison with the New Source Performance Standard averaged 0.71 lb/MMBTU but the data were widely scattered. The standard is 0.7 lb per million BTU of heat input. On a heat input basis, the NOx levels of the emissions were substantially higher with the low sulfur coal than with the coal with normal sulfur content. The parameters having a potential impact on Demo. Unit performance compared with those at normal operation are as follows:

	1% Sulfur	3% Sulfur
Average Load, MW	87.9	90.0
NOx in Flue Gas, ppmv	403	114
NOx in Flue Gas, lb/hr	693	188
NOx/SO_2, mol NO_2/mol SO_2	0.580	0.059

3.6.5.2 Potential Effects on Demo. Unit Performance

A ten-fold increase over the normal sulfur tests of the mol ratio, NOx/SO_2, was indicated for the low sulfur tests. However, it was pointed out in section 3.2 that only 5-10% of the NOx may be NO_2. Therefore, oxidation in the absorber to the more inactive sodium salts might not be significantly increased by the increase in relative NOx levels as represented by the NOx/SO_2 ratio. During the Demonstration, NO and NOx concentrations will be monitored continuously and a better indication of oxidation effects by NO_2 will be gained at that time.

3.6.6 Particulate Emission Levels

Relevant data are included in Table B-37.

3.6.6.1 Comparison with Design

All tests exceeded the Federal New Source Performance Standard of 0.10 lb/MMBTU. On an equivalent heat input basis, the particulate levels for the low sulfur test series were only slightly lower than for the test series at normal operating conditions (0.60 lb/MMBTU versus 0.70 lb/MMBTU). Comparison with normal operation and with Demo. Unit design conditions is as follows:

	1% Sulfur	3% Sulfur	Design
Average Load, MW	87.9	90.0	92
Grain Loading, gr/acf	0.18	0.24	0.20
Mass Rate, lb/hr.	643	704	580

3.5.6.2 Collector Efficiency

Relevant data are shown in Table B-38.

Efficiencies were to be determined by the ASME sampling method which employs an in-situ filter for collection of the particulate followed by an unheated probe. Complete data was collected for only one test due to the condensation of and pluggage by solid material of the unheated section of probe outside the duct. Table B-38 is a compilation of the performance data of the ESP. Specific corona power, in watts/1000 cfm, was slightly higher than the corresponding results for the tests at normal sulfur levels. The comparisons are summarized as follows:

	Specific Corona Power, watts/1000 cfm	
Nominal Load	1% Sulfur	3% Sulfur
46MW	133	101
92MW	65	41
115MW	61	47

For a given flue gas profile, collector efficiency is normally expected to increase with specific corona power requirements. However, lower collection efficiencies are suspected.

3.5.6.3 Particle Size

Relevant data are included in Table 3-23 and on Figures B-10 through B-13.

Size distribution of the particulate matter outlet the precipitator was determined by the same in-situ method employed during the normal sulfur tests. On the average, 50% of the particles were less than 3.0 micron diameter. This approximates results of the normal sulfur tests. Sampling difficulties were discussed in 3.2.6.7.

TABLE 3-23

PARTICLE SIZE DATA

Off-Normal Conditions

(Low Sulfur Coal)

TEST NO.	LOAD GROSS (MW)	MASS MEDIAN DIAMETER (MICRONS)	SOOT BLOWING STATUS	AS FIRED COAL SIZE, % THRU 200 MESH
27	44.5	3.6	Off	63.9
28	89.8	3.0	Off	59.8
29	88.7	1.9	On	65.0
30	87.5	1.6	Off	62.5
31	88.2	3.9	On	64.2
24	111.2	4.3	Off	60.6
25	111.6	4.0	Off	66.8
33	108.9	3.0	Off	65.8
35	110.1	1.8	Off	68.6

3.6.7 Trace Element Emissions

Relevant data are included in Tables 3-17, 3-18, B-39, B-40 and B-41.

Concentrations of 16 metals were determined on ash in the coal and on the fly ash in the outlet duct. Table 3-17, included in section 3.2, shows comparative tabulations in decreasing order of concentration in the 1% sulfur coal. Differences in the trace metal content of the two coals are readily apparent. Table 3-18, included in section 3.2, provides the same comparison for the fly ash in the outlet flue gas. Again, several differences exist in the emission concentrations from burning the two coals.

No concentrations of mercury or the halogens (F and Cl) were determined on the flue gas for the low sulfur coal tests. However, these concentrations were analyzed on the coal. The concentrations compared with the corresponding concentrations in the 3% sulfur coal were as follows:

	1% Sulfur	3% Sulfur
Hg, ppmw	<0.001	0.166
F^-, ppmw	132	93
Cl^-, ppmw	800	400

4.0 TEST PROBLEMS

The problems encountered can be assigned to three general categories:

- Operational
- Adverse weather conditions
- Data collection and data reduction problems

The involved NIPSCO personnel cooperated fully with TRW field test personnel to see that the Mitchell No. 11 boiler was operating at the test conditions requested, was operating at steady state, and that the NIPSCO instrumentation used to collect Baseline Test data was calibrated as requested. Thus, operational problems impacting on the test schedule or test results were largely unavoidable. Field tests were conducted during the spring of 1974 and 1975 and delays caused by adverse weather conditions were due entirely to heavy rains or electrical storms. Several testing and data reduction problems were encountered, although considering the large amount of data collection involved, problems in these areas were to be expected.

In the following subsections, the problems encountered and their effect on schedule and on test results are discussed. The information is presented as part of the documentation of the test data but it will also be useful as part of the site-dependent experience to be utilized in the performance of the subsequent Acceptance Test and Demonstration Test.

4.1 OPERATING PROBLEMS

The field test log is shown in Appendix D.

4.1.1 General

A major problem encountered was power demand which severely limited availability of the boiler operating at 46MW. Due to this, it was necessary to alter the test schedule and to cancel one of the 46MW tests for Test Series 5 (low sulfur). A delay of one-half day occurred due to the low load limitation. The other major problem was the unavailability of a high sulfur coal (4-5% S) for testing at that operating condition. NIPSCO has been requested to continue its search for high sulfur coal supplies for the Demonstration Test. Unavailability of the boiler for the full scheduled test period resulted in the field tests being carried out in two phases. Thus, Test Series 1 and 2 were conducted during May 1974 and Test Series 3 and 5 were conducted during April 1975. Although this had a significant impact on test scheduling and reporting, it was not considered a major problem. Minor differences in operation and their effects on the test results are described in section 3.0.

4.1.2 Test Delays

Delays caused by the boiler not being available were as follows:

a. Coal mill problems = 1.5 days

b. FD fan damper = 0.5 day

c. Low load limitation = 0.5 day

d. Loss of coal reclaiming hopper due to coal slide = 4.0 days

Following availability of the reclaiming hopper (item d), it was decided to begin filling the bunkers with one percent sulfur coal. This resulted in the cancellation of one test of Test Series 3 (miscellaneous tests) which was to be run with normal coal (3% S).

4.1.3 Boiler Limitations

Not all boiler limitations had discernable effects on test performance. However, for documentation purposes, all limitations are included in the discussion to follow.

Test 1 was run at 46MW with only two of the four coal mills operating. No effect on test results was noticed.

Tests 2 through 7 (92MW) were run with only three coal mills operating. Again, no effect on test results was noticed but it was an objective of the Test Plan to evenly distribute coal firing by using all four mills.

Tests 8 through 21 were run without complete control of the FD fan dampers. This resulted in a load limitation of 110MW for the special tests using a high excess of combustion air (Tests 14, 15, 18).

Tests 14 through 21 were run with hot bearing temperatures and more than normal vibration on the west ID fan. This fan was finally forced down following Test 21. Because of an impending labor contract deadline at NIPSCO, testing was interrupted. This resulted in delay of the miscellaneous tests for a full year. Completion of the miscellaneous tests as scheduled would have prevented the need to change coal types between Test Series 3 and Test Series 5.

All tests of Test Series 3 and Test Series 5 which were scheduled to be at full load were limited to about 111MW due to a feedwater pump limitation.

During Tests 26 and 27 (46MW), BFP 11W, FD fan 11W, and Mills 3 and 4 were down. The gas recirculating damper was open 20% to control temperatures.

During Test 27, coal sulfur content was significantly higher than one percent, suggesting contamination.

During Tests 28 through 31, short outages of the coal mills occurred due to feed hopper pluggage by wet coal. Test 30, scheduled at 92MW, was load limited to 80MW for 35 minutes due to wet coal.

4.2 ADVERSE WEATHER PROBLEMS

Delays totalling five days were caused by heavy rains or electrical storms. The heavy rains also contributed to a coal slide into the reclaiming hopper which delayed testing an additional four days.

4.3 DATA COLLECTION AND REDUCTION PROBLEMS

4.3.1 General

The only scheduled delays due to test equipment problems were delays at the beginning of each test phase totalling one day. Data collection problems resulted in the loss of samples or in aborted elements of a test during several tests. However, no tests were completely aborted or delayed by as much as one-half day as a result of sampling or data collection problems. The problems associated with data collection and reduction are categorized as follows:

- Data collection
- Analytical
- Data reduction

4.3.2 Data Collection

Comparison of the results of analyses of coal composite samples with the corresponding results of individual samples shows poor agreement. The best explanation for these differences is that the composite sample lacked representativeness due to improper reduction of the gross samples to a laboratory sample size, see 3.1.6.3.

Steam flow measurements were consistently higher than feedwater flow measurements, as described in 3.1.4. As a result, it became necessary to use feedwater rates for all efficiency and energy balance determinations.

During Test Series 5, with low sulfur coal, particulate collection by the ASME method had to be abandoned due to pluggage of the unheated section of the sampling probe with a non-ferrous solid material. Since the ASME method employs an in-situ filter upstream of the plugged section, it is assumed that the solid formation is in a gaseous state at the duct temperatures. Problems were encountered primarily at the air heater inlet at 627 to 690°F duct temperature but also at the ID fan outlet at duct temperatures of 290 to 340°F. Without particulate results by the ASME method, the dust collector performance could not be evaluated adequately.

Some sulfur oxide samples were lost due to sample blowback created by the stack pressure pressurizing the sample collection apparatus after pump shutdown. The sample was then pushed back through the impingers when they were disconnected from the probe. This problem was solved by slowly bleeding the pressure off before disconnecting from the probe. Purging was accomplished using ambient air drawn through activated charcoal to avoid sample bias due to the high ambient SO_2 levels.

Particle sizing results were influenced by stage to stage carryover of the sample. There was a significant fraction of large particles overloading the first stage during several of the tests. Although an inherent problem with the Brink cascade impactor (as well as other inertial impactors), stage overloading is not so serious a problem as to justify a change in methodology. The alternatives have significant problems which detract from their use. Any method that bases the results on a physical count (optical microscopy, scanning electron microscopy, automatic optical counters) does not really identify the mass diameter, which is critical in the effectiveness of most particulate collection devices such as scrubbers and inertial collectors. Additionally, in most cases there is the problem of taking a portion of a sample and assuming it to be representative of the original source of the sample.

To perform a set of off normal tests at higher than normal flue gas volumes, access doors were opened at the air heater outlets to simulate additional inleakage. During the first of three replications (Test 19), the doors were only partially open and the amount of excess inleakage was inadequate. Thus, only two out of the three tests were at the desired operating conditions.

Measurements of CO and total hydrocarbons during Test Series 3 were not valid due to ambient air leakage into the sampling system.

The physical locations of the flue gas sampling positions were less than ideal. The most obvious problem arising from these factors has been the flow data. Values at the outlet are believed to be relatively accurate, especially when Boiler No. 6 was down or at reduced load, and this is confirmed by theoretical and calculated values, see Table B-32. The inlet measurements of velocity are not at all reliable and, in fact, many of the points tested gave negative flow values, an indication of the extreme turbulence at this location. In one particular test, test 26, the west FD fan was down and during this test the velocity profile of the majority of the points tested on the west side of the inlet APH duct were negative. Due to these erratic flow measurements, calculated values were used for analysis of the data.

Additional problems at the outlet location were encountered:

a. Flue gas leaks. Due to the positive pressure in the duct at this location and the leaks around the dampers in the immediate area of the sampling location, as well as escaping flue gas during the opening of ports to change probe locations, high ambient SO_2 levels were encountered. The test team members used respirators to combat the problem, but eye irritation and respiratory irritation remained a significant problem throughout the tests.

b. Vertical sampling/long probes. This problem area is not uncommon in source tests, and had little effect on results, but does make the test performance more difficult and demanding.

4.3.3 Analytical Problems

A problem was encountered in the analytical procedure for SO_2/SO_3 due to the relatively high sulfur content in the sample. The end-point was very indistinct and difficult to reproduce. This was overcome by two steps:

1. Using a smaller sample aliquot, thus diluting it by a factor of approximately 5.
2. Diluting the titrant 1:10, to make the amount of titrant used significant enough to more easily read from the buret.

These changes produced a much more distinct end-point and no further problems were encountered in analysis.

Fluorides and chlorides in the coal, ash or flue gas were analyzed by different methods and at resultant different degrees of accuracy depending on the sample source. The varying levels of sensitivity from coal to ash to flue gas prevented the estimate of close approximations of the true distributions of fluoride and chloride between the ash and the flue gas.

4.3.4 Data Reduction Problems

The problems encountered in obtaining a valid sulfur mass balance are described in detail in 3.2.4.1.

Certain assumptions had to be made for calculating ash mass balances. This was due in part to lack of sampling access between the air heaters and the ESP and to the generally poor sampling locations for particulate and for velocity traversing at the air heater inlet and at the ID fan outlet.

The computer program was developed primarily for efficiency and heat rate results. A number of additional calculations which were needed for evaluation of the data had to be done manually, which was time consuming and labor intensive. These additional calculations can easily be incorporated into the existing computer programs. Some minor errors in the computer program turned out to be troublesome due to their effects on a large number of calculated results. For example, as fired coal analyses were used incorrectly. This affected practically every result of the computer program.

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5.0 RECOMMENDATIONS

5.1 SCOPE

As part of the approach to the baseline testing of the T&E program, it was intended to utilize the site-dependent experience gained during the Baseline Test for initiating improvements in the subsequent Acceptance and Demonstration tests. Benefits from the experience gained might include limited changes in the test plans as well as improvements in technique or methodology. In section 4.0 the problems encountered during the Baseline Test are described. Recommendations will follow which are intended to minimize or eliminate several of these problems.

5.2 TEST TECHNIQUES AND METHODOLOGY

Attention will be focused prior to further testing on improvements in the techniques for preparing composite samples. It is recommended that significant modifications in the methodology be employed. These are:

1) Modify the ASME particulate sampling method to provide a heated probe which would feed a set of impingers in hopes of avoiding aborted tests due to probe pluggage during operation with off normal coals. Conduct a pretest with this modified sample train. If not successful, discontinue use of the ASME method.

2) Modify the method for determining NOx according to recommendations recently described in the literature(10). The modifications include evaporating the sample in new unetched borosilicate dishes; adding only enough sodium hydroxide to neutralize the acidic solution of nitrates; adding excess of ammonium hydroxide prior to the spectrophotometric measurement; and reading the absorbance at 405nm as opposed to 420nm.

3) Review test procedures for chloride to see if more consistent levels of sensitivity are possible for coal, ash and flue gas.

4) Analyze samples prior to the Acceptance Test to obtain optimum agreement of oxygen concentrations between the Orsat determination and by analyzer.

5) Expedite turnaround of coal sample results in order to calculate efficiencies, flow rates, sulfur balance, etc. in the field.

5.3 TESTS WITH HIGH SULFUR COAL

The Demonstration Test Plan calls for a series of 12 tests with a high sulfur coal (4-5% S). The high sulfur coal was not available for the Baseline Test. It is recommended that every effort be made to obtain a coal of this type in time for the Demo. No. 2 spot test, scheduled for the sixth month of the Demonstration.

5.4 CALIBRATION OF STEAM AND FEEDWATER METERS

It is recommended that NIPSCO recalibrate the total steam and feedwater meters. Significant differences in flow rates measured by these meters were found.

5.5 INTRODUCTION OF OFF NORMAL EXCESS COMBUSTION AIR

Improved methods for obtaining higher than normal excess combustion air will be explored.

5.6 DATA REDUCTION

It is recommended that the computer program for evaluation of the spot test results be expanded and upgraded. It is possible to incorporate a number of additional calculations into the computer program, thus reducing the time and the labor for the data reduction.

6.0 REFERENCES

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7. ASME Power Test Codes, Test Code for Dust-Separating Apparatus, PTC 21-1941, American Society of Mechanical Engineers, New York, New York, (1941).

8. Oglesby, S., et al, A Manual of Electrostatic Precipitator Technology - Part I - Fundamentals, Prepared for National Air Pollution Control Administration, APTD - 0610, (1970).

9. Deutsch, W., Ann. der Physik, 68, 335, (1922).

10. Robertson, D., Improvements in Phenodisulfonic Acid Method for Determination of NOx, Environmental Science and Technology, Vol. 9 No. 10, October 1975.

11. Acceptance Test Plan for the Test and Evaluation Program for the NIPSCO/Davy/Allied Demonstration Plant, Prepared by TRW, Transportation and Environmental Engineering Operations, Vienna, Virginia, (1976).

12. Weinstein, L.H., et al. "A Semi-Automated Method for the Determination of Fluorine in Air and Plant Tissues," Contrib. Boyce Thompson Inst., 22 (4), 207-220 (Oct.-Dec. 1963).

13. Instruction Manual for Fluoride Electrode, Orion Research, Inc., Cambridge, Mass.

14. "Colorimetric Method for Arsenic in Coal," U.S. Bureau of Mines Report 7184 (1968).

APPENDIX A. BOILER DESCRIPTION

BOILER DESCRIPTION

TYPE AND EXPECTED CONDITIONS

Unit No. 11 is a balanced draft wet bottom radiant wall-fired reheat boiler which was manufactured by Babcock and Wilcox and placed into service in 1969. The unit can develop a maximum continuous steam capacity of 821,000 lbs/hr with a corresponding turbo-generator output of 115 megawatts. The steam parameters controlled are 1870 psi, 1005°F secondary superheater outlet, 1005°F reheat. Nominal operating values at several load levels are shown in Table A-1. A flow configuration of the boiler unit and major auxiliaries is shown in Figure A-1.

TABLE A-1

MITCHELL NO. 11 NOMINAL VALUES

	P	T	h	F	P	T	h	F	P	T	h	F
Units	PSIG	°F	BTU/lb.	10^3 lb./hr.	PSIG	°F	BTU/lb.	10^3 lb./hr.	PSIG	°F	BTU/lb.	10^3 lb./hr.
% Load	100				60				40			
Locations: Sec. S.H. Outlet	1800	1000	1460.4	702.79	1800	1000	1460.4	402.02	1800	1000	1460.4	292.33
R.H. Inlet	466.6	665	1302.3	766.92	277.5		1329.4	540.3	186.6		1334.2	235.16
R.H. Outlet	437.6	1000	1527.4	766.02	239.6	1000	1529.1	540.3	180	1000	1520.9	235.16
Extraction to #4 Htr.	227.2		1402.4	31.08	177.3		1469.5	21.62	86.4		1460.1	8.37
FW Entering Econ.		492.0	466.8	702.79		438	413.5	402.02		377.6	367.2	292.33
BFW #6	184.0	333.2	303.3		82.1	313.0	283.9		41.2	269	237.8	
BFW After BFW Pump	2552	336.4	331.8		2370	379.1	353.1		1980	276.1	247.	
BFW #7 Entering #6 Htr.		363.7	309.5			362.7	337.8			331.4	302.5	
Drain #7B	255.8	364.6	277.8	46.29	160.4	325.2	295.7	67.67	80	235.5	296.4	25.32
Drain #7B from #6 Htr.	461.5	392.2	367.7		300.5	300.6	347.3		177.1	371.8	285.8	
Absorption			1029.6				1066.8				1133.2	
Absorption -- R.H.			178.0				194.7				216.7	
Absorption -- S.H. Spray			1389.6				1107.3				1222.4	
Absorption -- R.H. Spray			1270.6				1231.				1285.6	
Stm. To #5 Htr.		665	1302.3	65.23			1329.4	46.25			1334.2	17.66
Radiation Loss	0.23%											
Carbon Loss	0.3%											
Margin	1.5%											

Legend:

P = Pressure
T = Temperature
h = Enthalpy
F = Flow rate

Source: [illegible]

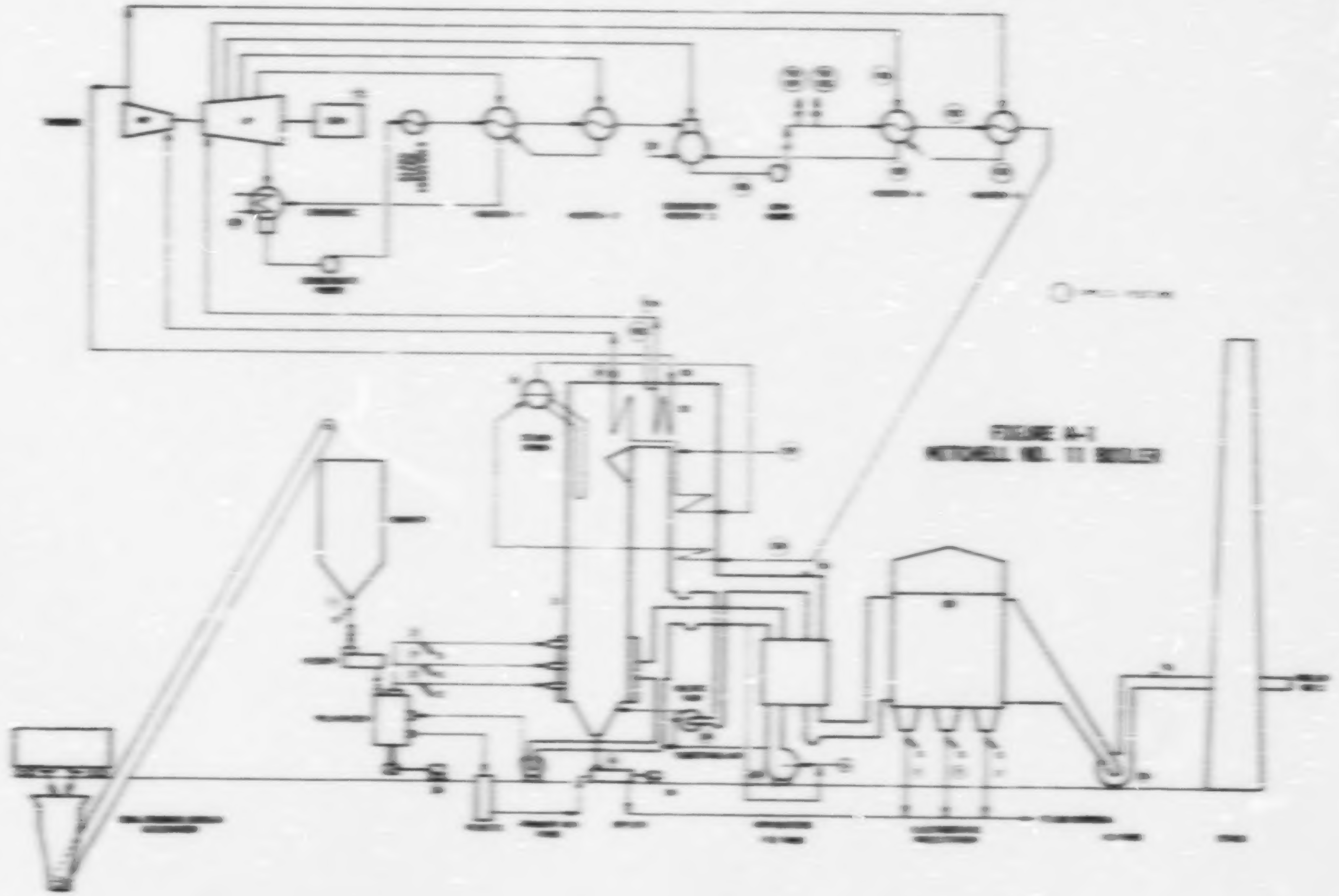

FIGURE A-1
MITCHELL NO. 11 BOILER

LOCATION

The D. H. Mitchell Station is located near the extreme northwest city limits of Gary, Indiana and fronts on Lake Michigan near its extreme southern end. Unit No. 11 is the easternmost of four (4) coal fired boilers at the station. Access to the station is by Clark Road which intersects U.S. Highway 12.

Lake Michigan is the source and receiving body for the cooling water. Elevation at grade is 586.5 feet above mean sea level. Elevation above normal lake level at grade is eight feet. Atmospheric temperatures are as follows:

Summer average 75°F, Peak 100°F

Winter average 30°F, Low -8°F

FUEL

Generally, Mitchell No. 11 burns a mixture of pulverized coal and petroleum coke. To correspond to general practice of the utility industry and to avoid homogenity problems, coal only is recommended for the baseline test series. The coal normally burned is a high volatile bituminous, H.V.C. rank (ASTM D388 designation) obtained from the No. 6 bed located in Southwest Illinois*. Typical analyses, shown in Table A-2, is believed representative of the type coal normally burned.

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*St. Clair, Perry and Jackson Counties (4 mines).

TABLE A-2
COAL USED AT NIPSCO MITCHELL NO. 11, DECEMBER 13/15, 1972

AS REC'D.	#1	#2	#3	#4	AVG.
H_2O %	14.00	12.00	13.60	14.90	13.62
Ash	10.32	9.01	9.53	9.05	9.48
Vol.	34.87	31.23	33.94	32.13	33.04
F.C.	40.81	47.76	42.93	43.92	43.85
HHV, Btu.	10656	11273	10958	10859	10936
S	2.81	3.12	2.95	2.88	2.94
Alk.	0.16	0.14	0.16	0.13	0.15
C	59.98	60.47	56.49	60.40	59.85
H	4.23	4.27	4.16	4.20	4.21
N	0.23	0.22	0.22	0.30	0.37
Cl	0.09	0.07	0.03	0.06	0.06
O	8.33	10.34	11.02	8.13	9.46
In Ash:					
P_2O_5 %	0.14	0.10	0.10	0.14	0.12
SiO_2	45.12	45.42	47.82	46.32	46.32
Fe_2O_3	17.45	17.70	16.90	17.00	17.26
Al_2O_3	17.59	19.09	19.09	19.43	18.80
TiO_2	0.86	0.93	0.82	0.93	0.88
CaO	7.85	7.00	6.45	6.75	7.01
MgO	1.00	1.00	1.00	1.00	1.00
SO_3	6.86	6.41	5.15	5.48	5.97
K_2O	1.76	1.76	1.82	1.82	1.79
Na_2O	0.39	0.44	0.50	0.20	0.38
Undetermined	0.98	0.15	0.35	0.33	0.45
ppm in Ash:					
Mn	825	610	575	530	635
Cu	610	520	495	515	535
Zn	375	365	300	990	507
Ni	600	450	600	600	612
Cr	475	335	335	335	370
Pb	660	675	620	610	639
ppm in Coal:					
Hg	0.24	0.25	0.36	0.27	0.28

Reference: "Dust Collector Studies"
Northern Indiana Public Service Company
D.H. Mitchell Station No. 11
P.O. No. 5955-54 - December 13-15, 1972

F.R. Kin & Associates, Incorporated
P. O. Box 655
Chicago Heights, Illinois 60411

FUEL HANDLING

Coal is transferred from rail cars or storage piles through a crusher to screens which classify to one inch maximum. This coal is transported by conveyor to a bunker of about 2000 tons capacity. Coal flows by gravity through four fill pipes, 24 inch diameter, to four coal feeders. Raw coal will be sampled from the gravity feed pipes.

The four fill pipes run full and thus act as a seal leg for pressurization of the feeders and pulverizers. The raw coal flows across four weigh feeders and then by gravity to four pulverizers.

FUEL FIRING

General

The boiler front wall contains 12 circular burners. Four pulverized coal mills each feed coal-air (77% through 200 U. S. mesh) to three burners. Excess combustion air is normally 19% (design value) but higher at low loads. Each coal pulverizer receives coal from a separate gravimetric coal feeder mounted on the operating floor between the overhead coal bunkers and the coal pulverizers. At low load, the option exists of turning off one feeder.

The normal operating capacity of Mitchell No. 11 ranges from 46 to 115 megawatts and the 1972 annual average load factor was about 80 percent* or 92 megawatts. During normal operating conditions, the load is changed at the rate of 1.0 megawatts per minute. The load can be changed from a hot initial condition at the faster rate of 3.3 megawatts per minute up or down if required. From a warm initial condition, the load can be changed at the rate of 1.6 megawatts per minute up or down if required.

Equipment Descriptions

Coal Feeders(4). These units are Stock Equipment gravimetric coal feeders, pressurized, which gravimetrically measure coal feed rate. Maximum capacity of each is 60,000 lbs/hr.

Pulverizers(4). B&W Model EL70 ball mills, ball and race type, medium speed. New ball diameters are 11 1/4" and wear is to 7". Primary air is supplied by a blower for each mill. Power input, including blower, is 14 KW hr/ton coal. Additional relevant data is listed in Table A-3.

Burners(12). B&W circular register, 36" diameter with steaming capacities of 91,200 lb/hr., each burner. Igniters are gas fired. The fuel feeding pattern is shown in Figure A-2. Connections for sampling "as fired" coal are available on each feed pipe.

Air Supply. Two forced draft fans are provided as well as four primary fuel-air fans. See Table A-4 for fan information. In

---

*1972 historical data.

TABLE A-3

PULVERIZED COAL EQUIPMENT DATA

Number of mills per boiler	4
Type of mills	EL-70
Size (manufacturer's rating), tons per hour	17.03 - 50 grind 70%/200 Mesh
Type of fans (blower or exhauster)	Blower
R.P.M. of blowers	1,800
Assumed grindability of coal	50
Maximum temperature of preheated air that can be used in mill	650°F

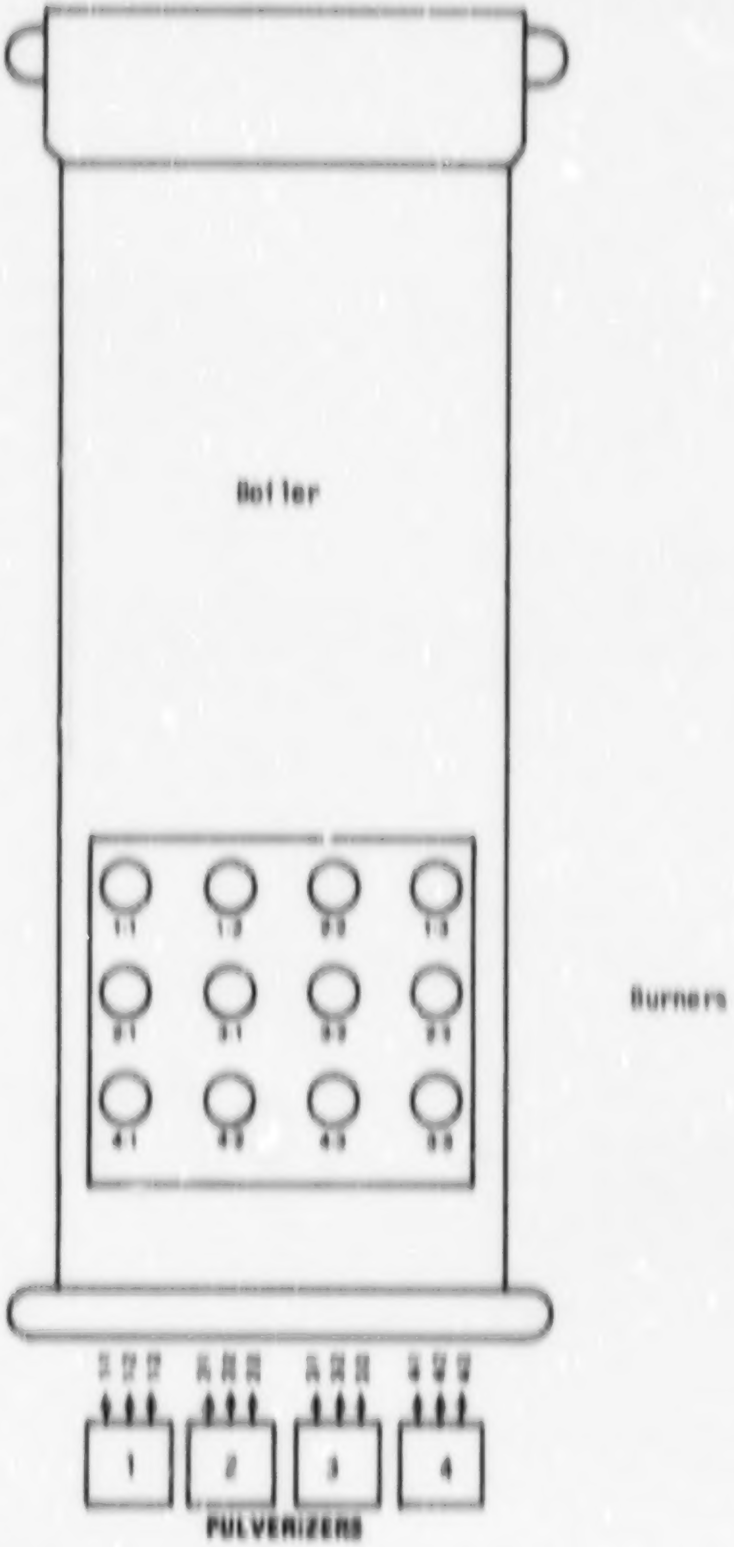

Boiler
1-1
1-2
2-2
1-3
2-1
3-1
3-2
2-3
Burners
4-1
4-2
4-3
3-3
1
2
3
4
PULVERIZERS

FIGURE A-2 FUEL DISTRIBUTION TO BURNERS

TABLE A-4

FANS AND PUMPS INFORMATION

Forced Draft Fans:

Manufacturer	American Standard
Number of Fans	2
Capacity @ 132°F	203,000 c.f.m.
Discharge Static Head	17.3 inches H_2O
Driver	A.C. 700 H.P. - 1185 R.P.M.

Induced Draft Fans:

Manufacturer	American Standard
Number of Fans	2
Capacity @ 289°F	228,000 c.f.m.
Static Head	-18.2 inches H_2O
Driver	Elliot 900 H.P. - 887 R.P.M.
Variable Speed Drive	American Blower Corporation

Boiler Feed Pumps:

Manufacturer	Ingersoll-Rand Company
Number	2
Type	10-Stage Barrel
Capacity	452,000 lb/hr. (1013 gpm)
Net Developed Head	2096
Variable Speed Drive	American Blower Corporation
Driver	West. 1750 H.P. - 3573 R.P.M.

case of draft unbalance due to malfunction, the boiler trips at one inch H_2O positive pressure with a two second time delay.

COMBUSTION CONTROL

The 721 analog system supplied by Bailey Meter is used.

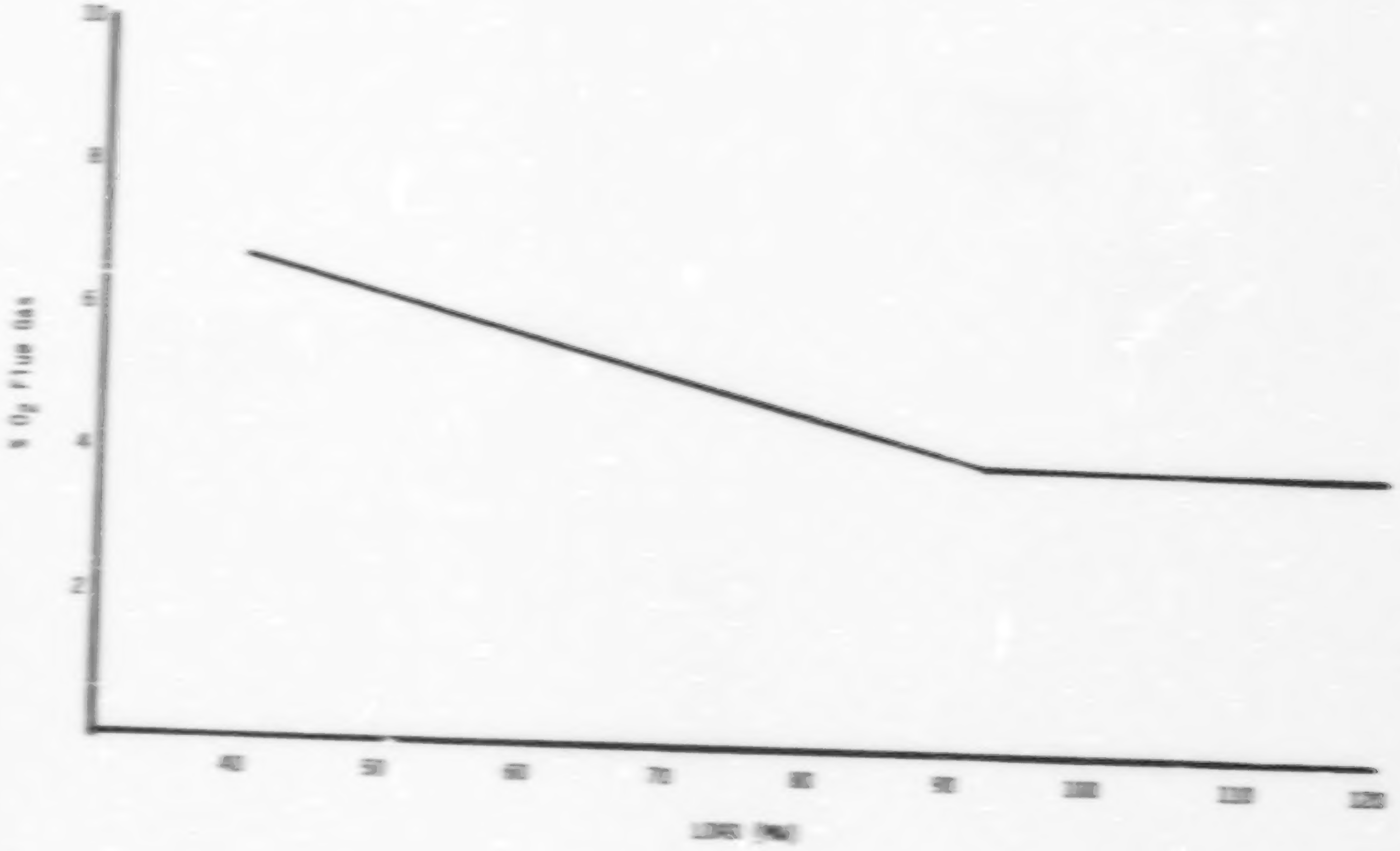
Fuel Control

1. MW output change affects turbine demand.
2. Turbine demand change affects steam control valves.
3. Change in steam control valve affects boiler pressure (measured as secondary superheater outlet pressure) and steam flow rates.
4. Change in summation of steam header pressure and flow rate affects mill demand.

Air Control

Primary combustion air flow is controlled by summation of steam flow and header pressure. Relevant sensors include air flow, air temperature, flue gas oxygen, steam temperature, steam flow and header pressure. Secondary combustion air is manually controlled by the control room operator. Figure A-3 is typical of the "load ramp" used for controlling excess air.

FIGURE A-3
OXYGEN VS. LOAD RAMP



FIRE SIDE CHARACTERISTICS

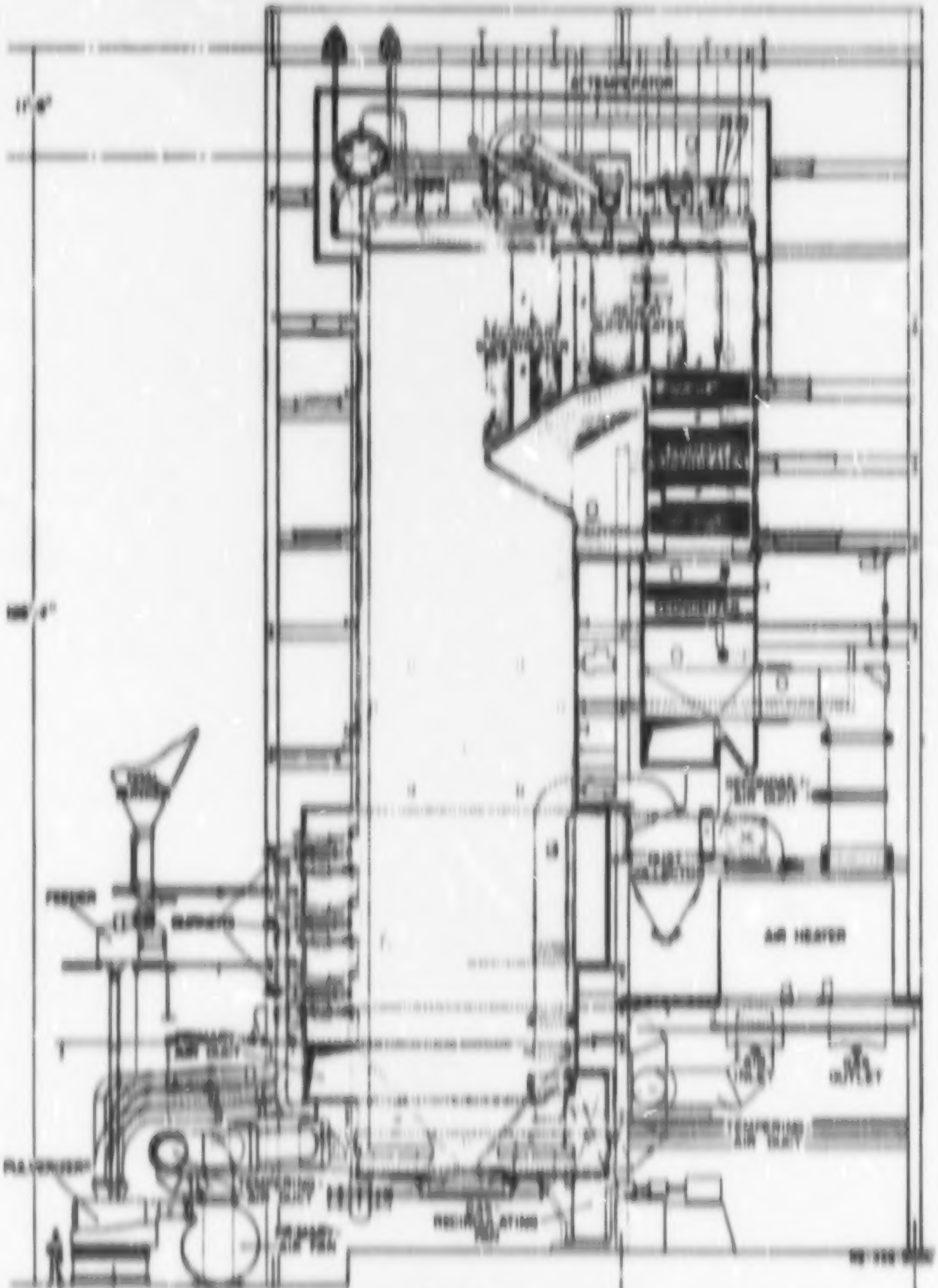
The furnace configuration is shown in the elevation drawing (Figure A-4). The furnace volume is 76,126 cu. ft. with effective heating surface as follows:

Reheat surface = 15,818 sq. ft.
Superheater = 54,130 sq. ft.
Reheater = 18,226 sq. ft.
Economizer = 9,550 sq. ft.
Air heater = 132,200 sq. ft.

Nominal flue gas temperatures at full load are 2,230°F (furnace exit), 1,900°F (superheater exit), 1,810°F (entering reheater), 1,290°F (leaving reheater), 695°F (leaving economizer). Gas recirculation from outlet the economizer, used mainly for startups, is provided.

The boiler is provided with a United Conveyor Co. ash handling system with a water-flooded ash hopper beneath the boiler. Pyrites rejection is combined with bottom ash and sluiced to the ash pond. Dust collector hoppers are emptied through rotary feeders and pneumatically conveyed out of the unit, and sluiced to the ash pond. Means for obtaining representative samples of pyrites and bottom ash are not available. The boiler is provided with a Copes-Vulcan Div. air energized wall deslagger and retractable soot blower system operating on a programmed daily cycle. The cycle is initiated by the control room operator. Wall blowers may be actuated independently at any time, to maintain steam superheat/reheat temperatures. Figure A-5 shows the relative positions of retracts and wall blowers. The normal soot blowing cycle requires about two hours to execute and is performed once a day, after midnight. For the test program, soot blowing can be scheduled at other hours and the cycle extended to three hours using manual actuation.

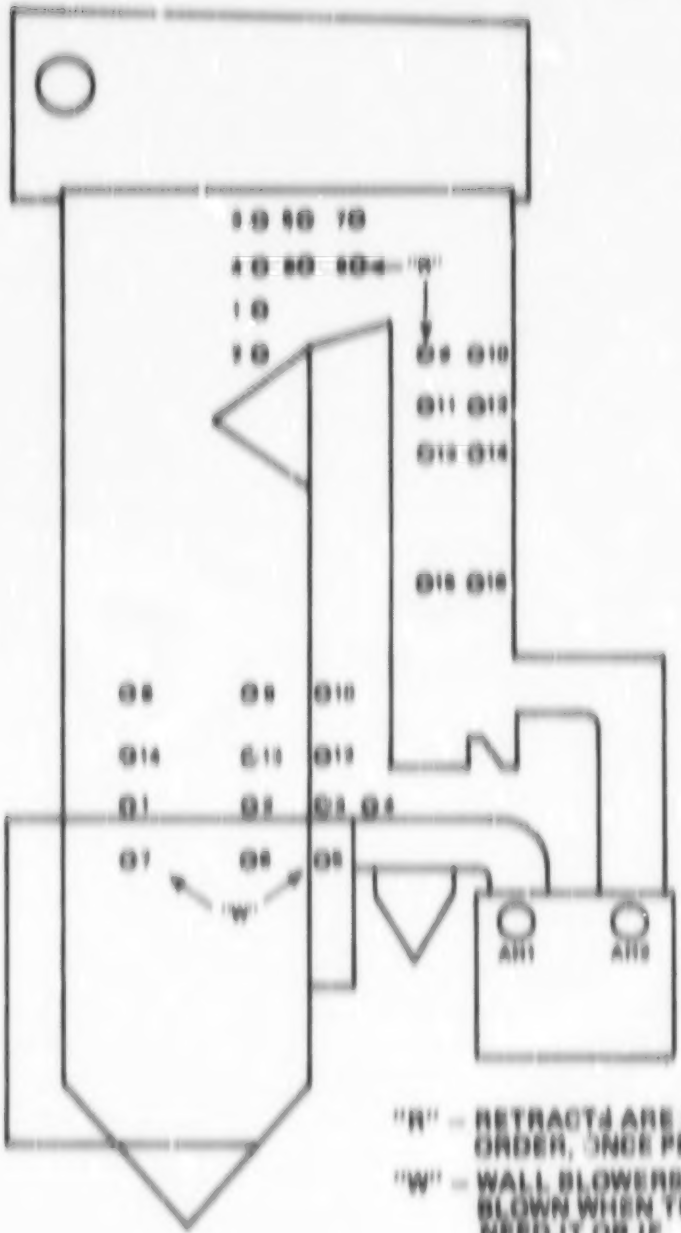
FIGURE A-4


FEEDER
BURNERS
AIR HEATER
PULVERIZER
PRIMARY AIR FAN
RECIRCULATING FAN
TEMPERING AIR DUCT
INLET
OUTLET

NORTHERN INDIANA PUBLIC SERVICE COMPANY
MITCHELL STATION - UNIT NO 11
GARY, INDIANA
B&W CONTRACT NO RB-456

FIGURE A-5

SOOT BLOWERS


3 5 7
4 6 8
"R"
1
2
9 10
11 12
13 14
15 16
8 9 10
14 11 12
1 2 3 4
7 6 5
"W"
AH1
AH2

"R" – RETRACTS ARE BLOWN IN ORDER, ONCE PER SHIFT.

"W" – WALL BLOWERS ARE BLOWN WHEN THEY NEED IT OR IF SCHEDULED, BEFORE RETRACTS, IN ORDER.

EVEN NUMBERED ARE RIGHT, ODD NUMBERED ARE LEFT.

STEAM SIDE CHARACTERISTICS

Steam conditions, superheat and reheat vs. load have been summarized in Table A-5. Heating surface areas are 54,130 sq. ft. (superheater), 18,226 sq. ft. (reheater). Boiler feed water pumps have been described in Table A-4. BFW is heated by a series of three water heat exchangers, deaerated, heating continued in two extraction-steam heaters, and then fed to the economizer. The secondary superheater outlet steam rate vs. KW relationship is as follows:

[illegible]ll load	6.6 lb/KWH
8[illegible] MWG	6.55 lb/KWH
46 MWG	6.35 lb/KWH

Attemperation spray water is withdrawn after the BFW rate meter and enters (1) hot reheat steam (2) primary superheated steam as controlled by the relevant sensors and controls. Nominal condenser exhaust pressure is 1.5" Hg. The condenser is a horizontal single-pass Ingersoll Rand unit with vertically divided water boxes, of phosphorized admiralty construction. Tube length is 30 ft. and surface area is 63,000 sq. ft. Once through cooling water from Lake Michigan is used.

The turbine-generator set is made by General Electric Co., is of the tandem compound single-flow reheat type, carries a nameplate rating of 115.1 MW, runs at 3600 RPM and has 6 extraction steam openings.

FEED WATER TREATMENT

Feed water treatment is of the conventional type with sodium sulfite deoxygenation and sodium phosphate alkalinity control. A deaerating feed water heater is provided. Water conductivity is monitored continuously and maintained at a low level by blowdown as needed. Blowdown rate can be measured by observing change in levels of demineralized water feed tanks.

AIR PREHEATERS

Two Ljungstrom type rotary air heaters, data shown in Table A-5, are provided. Flue gas and air inlet and outlet conditions are shown.

ELECTROSTATIC PRECIPITATOR

A cold end electrostatic precipitator, manufactured by American Standard Co., is in the flue gas stream between the air heaters and the induced draft fans. Descriptive data are shown in Table A-6.

TABLE A-5

REGENERATIVE AIR HEATER (DESIGN CONDITIONS)

MAKE: AIR PREHEATER CORP. TYPE: LJUNGSTROM SIZE: 22-VIR-66

HEATING SURFACE/UNIT SQ. FT.: 66,100 NO./BOILER: 2

% of Full Load	100	53	100
Evaporation, Lb. Steam/Hr.	821,000	437,400	Typical 821,000
Ambient Air Temp. °F.	80	80	
Air Leaving Heater Lb/Hr.	900,000	491,000	
Air Entering Heater Lb/Hr.	991,500	562,000	
Gas Entering Heater Lb/Hr.	1,091,000	633,000	
Gas Leaving Heater Lb/Hr.	1,182,500	704,000	
Temp. of Air Entering °F.	100	100	150
Temp. of Air Leaving °F.	602	607	
Temp. of Gas Entering °F.	697	668	
Temp. of Gas Leaving Uncorrected °F.	303	294	309
Temp. of Gas Leaving Corrected °F.	289	276	
Resistance, Air Side "H_2O	3.55	1.25	(Draft Loss)
Resistance, Gas Side "H_2O	5.80	2.35	
Total Pressure Diff. Across Heater "H_2O	16.85	9.10	

TABLE A-6
MITCHELL NO. 11 PRECIPITATOR SPECIFICATIONS

Design C.F.M.	410,000
T °F	290
Inlet gr/SCFD	3.5 to 6.5
ΔP "H_2O	0.4
Removal %	98.5
Rate Constant, Ft./Sec.	0.5
Plates, Ft.^{2}	58,240
Treatment Length, Ft.	17.3
# Fields	3
# Ducts	56 (@ 9")
Wire Ft.	40,320 (@ 7")
Wire Rating, ma./Ft.	0.08
Treatment Time, Sec.	3.2
Delivery	July 1969
# Plate Rappers	32
# Wire Vibrators	12
Hopper Ash Capacity Minimum	8 hrs.
# Bus Sections	6
Plate Height, Ft.	30
Energization	Half Wave
Rating KVP	70
Rating ma.	1800, 800, 600

Provision in the unit for another field, 6' treatment length above hopper can be added later

Expected removal w/field #1 only 87.7%

Expected removal w/fields #1 - 2 only 95.6%

Expected hopper #3 collects 2.8% of the dust

Ash removal pneumatically by 3 lines (fields 1, 2, 3)

No. ash hoppers - 12

FLUE GAS OUTLET

Description

Two induced draft fans are provided discharging into a common horizontal duct entering the base of the 235 ft. high stack shared with Unit No. 6. See Table A-4 for fan information. With retrofit of the WL/Allied unit, a quick acting damper, normally closed, is being installed in the common horizontal duct discharging to the stack. Part of the horizontal duct work is being replaced and redirected to the WL/Allied unit.

Sampling Conditions

Economizer exit gas samples are available at a position on a horizontal duct between a 90° turn after the economizer and a 90° turn before the air heater. Stack gas samples are available as described in Section 4.0.

APPENDIX B. BASELINE DATA BASE

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TABLE B-9

COAL QUALITY DATA

COMPOSITES OF 3% SULFUR TESTS

NORMAL OPERATION

TEST	1-10, 16, 17	1-10, 16, 17
SAMPLE	RAW COAL	AS FIRED COAL
High Heating Value, Btu/Lb	11300	11700
H_2O, wt. %	10.2	5.3
Ash, wt. %	10.1	11.8
Volatile Matter, wt. %	32.3	35.0
Fixed Carbon, wt. %	47.4	47.9
Sulfur, wt. %	2.9	3.3
Carbon, wt. %	63.4	65.8
Hydrogen, wt. %	4.4	4.6
Nitrogen, wt. %	1.3	1.4
Oxygen, wt. %	7.7	7.8
Chlorine, wt. %	0.03	0.02
Fluorine, ppm	1.16	0.76

TABLE B-10
COAL QUALITY DATA
COMPOSITES OF 3% SULFUR TESTS
OFF-NORMAL OPERATION

TEST	11-15, 10-21	11-13
SAMPLE	RAW COAL	AS FIRED COAL
High Heating Value, Btu/Lb	11400	11700
H_2O, wt %	8.5	5.6
Ash, wt. %	11.2	11.0
Volatile Matter, wt. %	33.5	36.1
Fixed Carbon, wt. %	46.8	48.2
Sulfur, wt. %	3.2	3.3
Carbon, wt. %	64.1	65.7
Hydrogen, wt. %	4.5	4.5
Nitrogen, wt. %	1.3	1.4
Oxygen, wt. %	7.2	8.8
Chlorine, wt. %	0.06	0.04
Fluorine, ppm	0.95	0.76

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TABLE 8-10

DRAFT LOSSES (In. W.C.)

NORMAL OPERATING CONDITIONS

Test	1	2	3	4	5	6	7	8	9	10	16	17
Air, Air Heater	2.2	4.7	4.5	4.0	4.6	4.1	4.0	4.8	4.4	4.8	1.9	1.8
Ducts and Dampers A.P.H. to Burners, Burners and Windbox	1.1	2.1	2.1	2.8	2.0	2.5	2.3	1.5	2.0	2.5	1.0	1.0
Total Air Resistance	3.3	6.8	6.6	6.8	6.6	6.6	6.3	6.3	6.4	7.3	2.9	2.8
Furnace and Convection Banks	2.5	2.9	3.5	2.8	3.3	2.8	3.5	5.0	3.6	5.0	3.2	2.4
Flues to A.H.	0.5	1.6	0.6	1.2	1.2	1.2	0.5	1.0	2.4	1.1	—[1]	0.6
Gas, Air Heater	3.0	4.6	5.1	4.5	4.4	4.5	4.4	5.6	5.9	6.3	3.0	3.0
Total Gas Resistance	6.0	9.1	9.2	8.5	8.9	8.5	8.4	11.6	11.9	12.4	—[2]	6.0
Total Boiler Resistance	9.3	15.9	15.8	15.3	15.5	15.1	14.7	17.9	18.3	19.7	—[2]	8.8

[1] Data not available.

[2] Incomplete data.

TABLE B-15

DRAFT LOSSES (In. W.C.)

OFF NORMAL CONDITIONS

Test	11	12	13	14	15	18	19	20	21
Air, Air Heater	4.7	4.7	4.5	5.3	5.2	4.6	4.3	4.4	4.6
Ducts and Dampers A.P.H. to Burners, Burners and Windbox	2.9	1.8	1.7	1.9	2.2	2.6	1.9	2.2	2.5
Total Air Resistance	7.6	6.5	6.2	7.2	7.4	7.2	6.2	6.6	7.1
Furnace and Convection Banks	5.0	4.2	4.2	4.7	4.8	4.5	4.5	3.8	3.8
Flues to A.H.	1.0	1.7	1.6	1.2	1.2	1.6	1.5	1.7	1.7
Gas, Air Heater	6.0	5.9	6.0	6.1	6.2	5.7	5.5	5.9	5.4
Total Gas Resistance	12.0	11.8	11.6	12.0	12.2	11.8	11.5	11.4	10.9
Total Boiler Resistance	19.6	18.3	18.0	19.2	19.6	19.0	17.7	18.0	18.0

TABLE 8-16

DRAFT LOSSES (In. W.C.)

OFF NORMAL CONDITIONS

(Low Sulfur Coal)

Test	26	27	28	29	30	31	32	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Air, Air Heater	5.0	5.0	3.4	2.9	4.0	1.5	3.3	2.3	4.1	4.1	3.2	4.9
Ducts and Dampers A.P.H. to Burners, Burners and Windbox	0.0	0.0	2.2	1.3	0.8	1.5	2.0	1.8	2.2	2.1	2.0	2.3
Total Air Resistance	5.0	5.0	5.6	4.2	4.8	3.0	5.3	4.1	6.3	6.2	5.2	7.2
Furnace and Convection Banks	2.7	2.7	3.2	3.5	3.8	4.0	3.8	3.7	4.5	4.0	4.7	4.3
Flues to A.H.	0.3	0.3	0.8	0.7	0.8	1.0	0.5	0.5	1.5	1.1	1.0	1.8
Gas, Air Heater	1.7	1.7	3.9	4.2	4.7	4.0	4.0	4.0	4.5	5.6	5.0	4.5
Total Gas Resistance	4.7	4.7	7.9	8.4	9.3	9.0	8.3	8.2	10.5	10.7	10.7	10.6
Total Boiler Resistance	9.7	9.7	13.5	12.6	14.1	12.0	13.6	12.3	16.8	16.9	15.9	17.8

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TABLE B-23

TRACE METALS IN OUTLET FLUE GAS PARTICULATE
ppm DRY WEIGHT BASIS

Normal Operation

Test	1,16,17	2,4,6	3,5,7	8,9,10	1-10,16,17
Test Condition	46-3-WO	92-3-WO	92-3-WI	115-3-WO	All (avg.)
Arsenic	87	62	85	88	76
Selenium	1085	106	118	43	830
Lead	326	142	137	142	187
Zinc	0	114	777	274	291
Silver	59	12	6	7	21
Copper	747	97	131	76	138
Manganese	227	215	205	204	213
Nickel	968	293	307	204	442
Tin	77	108	44	116	86
Cadmium	178	30	33	16	64
Chromium	2763	409	338	286	949
Calcium	10870	21856	17498	17886	17027
Beryllium	0	23	20	18	15
Vanadium	494	372	417	316	406
Magnesium	55	175	185	190	157
Antimony	4719	835	0	258	198
Iron	65136	54489	56313	53140	57257

TABLE B-24

TRACE METALS IN OUTLET FLUE GAS PARTICULATE

ppm DRY WEIGHT BASIS

Off Normal Operation

Test	11,12,13
Test Condition	115-3-WO
Arsenic	64
Selenium	163
Lead	139
Mercury	***
Zinc	387
Fluorine	***
Silver	8
Copper	79
Manganese	209
Nickel	194
Tin	58
Cadmium	21
Chromium	259
Calcium	15950
Beryllium	20
Vanadium	286
Magnesium	113
Antimony	564
Iron	47386

TABLE B-25

TRACE ELEMENTS IN AS FIRED COAL

ppm DRY WEIGHT BASIS
Normal Operation

Test	1-10,16,17	1,16,17	2,4,6	3,5,7	8-10
Test Condition	All	46-3-WO	92-3-WO	92-3-WI	115-3-WO
Arsenic	0.68	0.90	2.2	1.8	2.6
Selenium	<1	<1	<1	<1	<1
Lead	18	12	12	12	9
Mercury	0.16	0.14	0.13	0.10	0.11
Zinc	36	68	52	56	47
Fluorine	66	--	--	--	--
Silver	2	2	2	2	2
Copper	12	19	14	13	12
Manganese	40	50	42	42	43
Nickel	16	14	15	11	15
Tin	4	12	7	5	7
Cadmium	<0.5	<.5	<.5	<1	<.6
Chromium	56	66	43	46	45
Calcium	2462	2113	2100	1700	2625
Beryllium	1	<.5	2	3	1
Vanadium	22	18	22	12	17
Magnesium	75	102	83	88	68
Antimony	32	39	69	65	72
Iron	8415	8019	8239	8328	7332

TABLE B-26

TRACE ELEMENTS IN AS FIRED COAL

ppm DRY WEIGHT BASIS
Off Normal Operation

Test	11,12,13
Test Condition	115-3-WO
Arsenic	1.9
Selenium	<1
Lead	14
Mercury	0.1
Zinc	54
Fluorine	---
Silver	2
Copper	11
Manganese	48
Nickel	11
Tin	11
Cadmium	<0.5
Chromium	50
Calcium	2424
Beryllium	2
Vanadium	12
Magnesium	68
Antimony	40
Iron	10282

TABLE B-27

TRACE ELEMENTS IN RAW COAL COMPOSITES

ppm DRY WEIGHT BASIS
3% SULFUR

Test	11-15,18-21
Metal	
Test Condition	Off Normal
Arsenic	1.5
Selenium	<1
Lead	20
Mercury	0.5
Zinc	21
Fluorine	---
Silver	1
Copper	14
Manganese	40
Nickel	18
Tin	0
Cadmium	<.5
Chromium	53
Calcium	2762
Beryllium	2
Vanadium	17
Magnesium	83
Antimony	26
Iron	8555

TABLE B-28

TRACE ELEMENTS IN RAW COAL COMPOSITES

ppm DRY WEIGHT BASIS
3% SULFUR

Test	1-10,16,17
Metal	
Test Condition	Normal
Arsenic	1.5
Selenium	<1
Lead	20
Mercury	.09
Zinc	58
Fluorine	71
Silver	4
Copper	12
Manganese	53
Nickel	18
Tin	6
Cadmium	<.5
Chromium	60
Calcium	3875
Beryllium	7
Vanadium	18
Magnesium	170
Antimony	46
Iron	10660

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TABLE B-19

TRACE ELEMENTS IN AS FIRED COAL

ppm DRY WEIGHT BASIS
Off Normal Operation
(Low Sulfur Coal)

Test	24-25,33,35	30,32	29-31,34	26-27
Test Condition	115-S-WO	92-S-WO	92-R-WI	46-S-WO
Arsenic	<100	<100	<100	<100
Selenium	<200	<200	<200	<200
Lead	16	22	17	<10
Mercury	<10	<10	<10	<10
Zinc	30	37	40	33
Copper	14	16	13	16
Manganese	36	43	50	44
Nickel	32	20	27	22
Tin	1405	1625	14[illegible]	740
Cadmium	<10	<10	<10	<10
Chromium	17	12	11	11
Calcium	2950	3665	1355	3245
Beryllium	<10	<10	<10	<10
Vanadium	13000	14010	600	3820
Magnesium	1335	1365	950	830
Antimony	<10	<10	<10	<10
Iron	12500	19200	30550	90

TABLE B-40

TRACE METALS IN OUTLET FLUE GAS PARTICULATE

ppm DRY WEIGHT BASIS

Off Normal Operation
(Low Sulfur Coal)

Test	24-25,33,35	30,32	29,31,34	26-27	24-35
Test Condition	115-S-WO	92-S-WO	92-U-WI	46-S-WO	All (avg.)
Arsenic	<100	<100	<100	<100	<100
Selenium	<200	<200	<200	<200	<200
Lead	107	69	90	392	165
Mercury	<10	<10	<10	<10	<10
Zinc	1120	640	800	5580	2035
Copper	66	51	10	470	149
Manganese	123	140	140	780	298
Nickel	120	60	96	1050	329
Tin	510	100	230	1450	573
Cadmium	<10	<10	<10	<10	<10
Chromium	90	39	89	45	66
Calcium	3000	11890	1110	17160	8540
Beryllium	<100	<100	<100	<100	<100
Vanadium	<100	<100	<100	<100	<100
Magnesium	5390	1390	4420	26160	9340
Antimony	<100	<100	<100	<100	<100
Iron	84800	68500	97100	592600	210750

TABLE B-41

TRACE ELEMENTS IN RAW COAL COMPOSITES

LOW SULFUR TESTS

Test	24-35
Test Condition	Off Normal
Arsenic	<100
Selenium	<200
Lead	17
Mercury	<10
Zinc	20
Copper	13
Manganese	22
Nickel	36
Tin	1340
Cadmium	<100
Chromium	10
Calcium	3420
Beryllium	<100
Vanadium	7930
Magnesium	870
Antimony	<10
Iron	9630

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TABLE B-54
COAL QUALITY DATA
COMPOSITES OF 1% SULFUR TESTS
OFF-NORMAL OPERATION
(LOW SULFUR COAL)

TEST	24-35	24-35
SAMPLE	RAW COAL	AS FIRED COAL
High Heating Value, Btu/Lb	10700	11400
H_2O, wt. %	15.6	7.7
Ash, wt. %	10.5	12.6
Volatile Matter, wt. %	27.5	32.4
Fixed Carbon, wt. %	46.4	47.4
Sulfur, wt. %	0.8	1.0
Carbon, wt. %	61.1	64.3
Hydrogen, wt. %	4.1	4.6
Nitrogen, wt. %	1.2	1.4
Oxygen, wt. %	6.7	8.5
Chlorine, wt. %	0.08	0.07
Fluorine, ppm	115	--(1)

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(1) Insufficient Sample

FIGURE B-1
PARTICLE DIAMETER vs. CUMULATIVE PERCENT
LESS THAN STATED SIZE

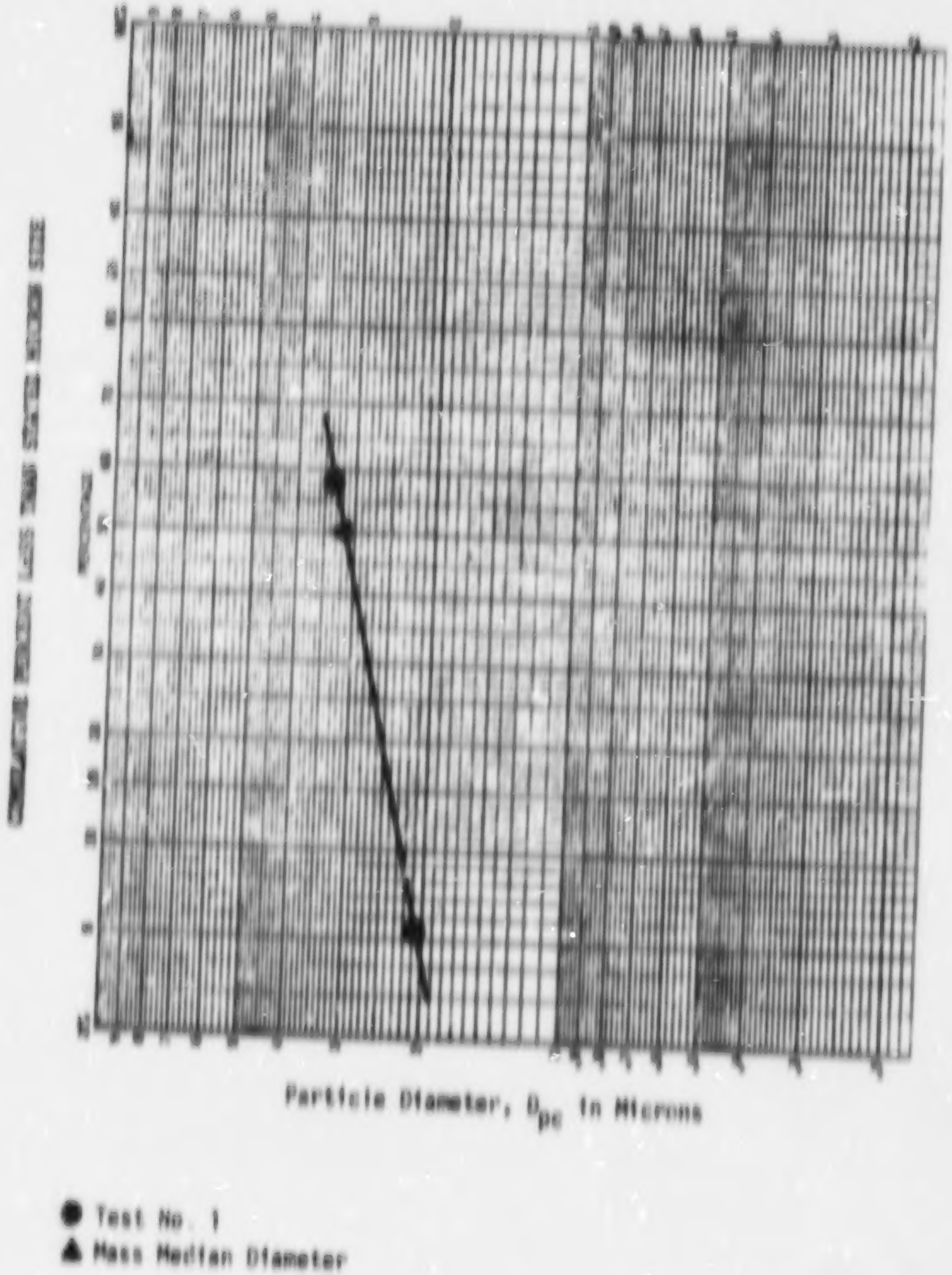
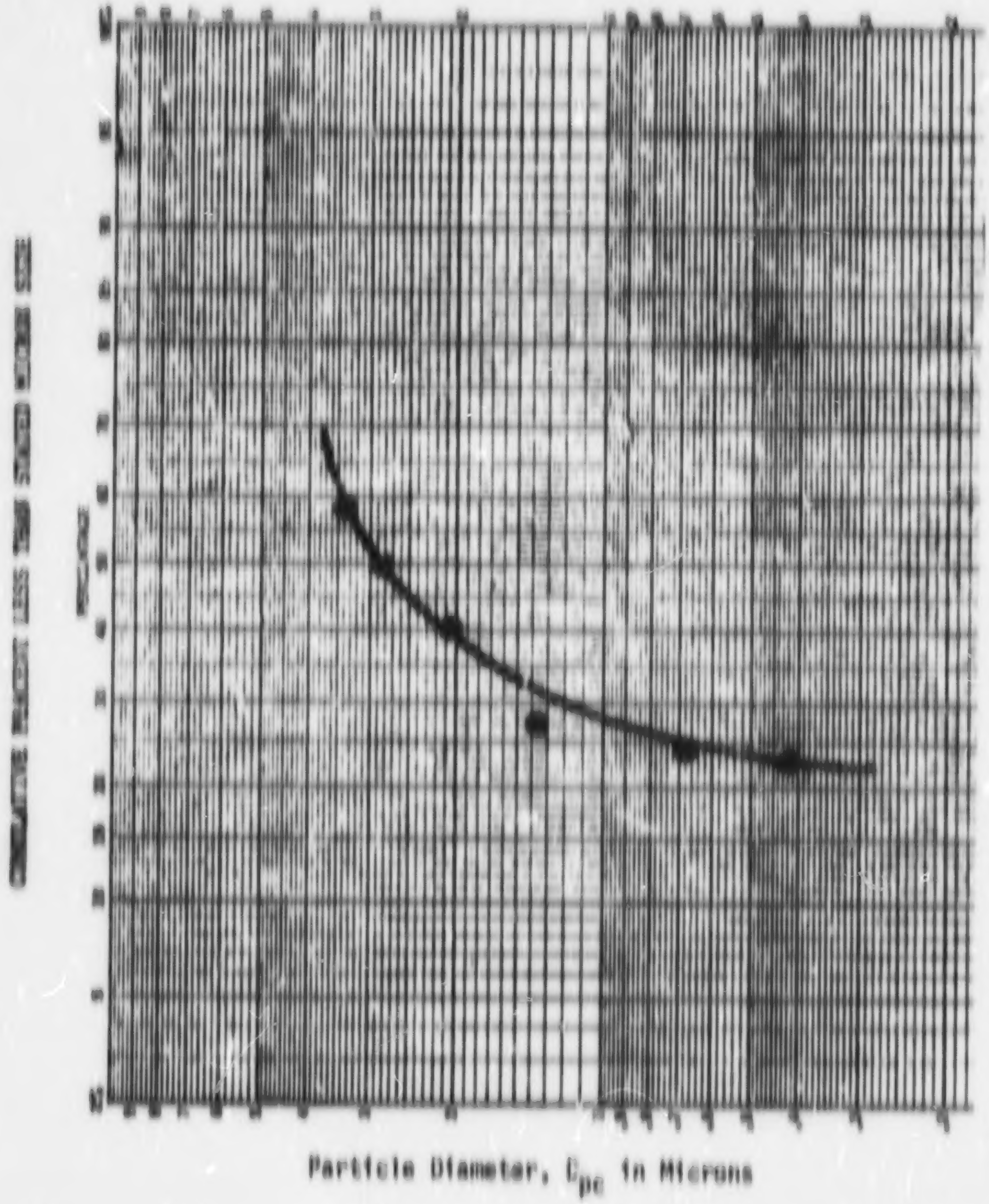


FIGURE B-2
PARTICLE DIAMETER vs. CUMULATIVE PERCENT LESS THAN STATED SIZE



● Test No. 2

▲ Mass Median Diameter

FIGURE B-3

PARTICLE DIAMETER vs. CUMULATIVE PERCENT LESS THAN STATED SIZE

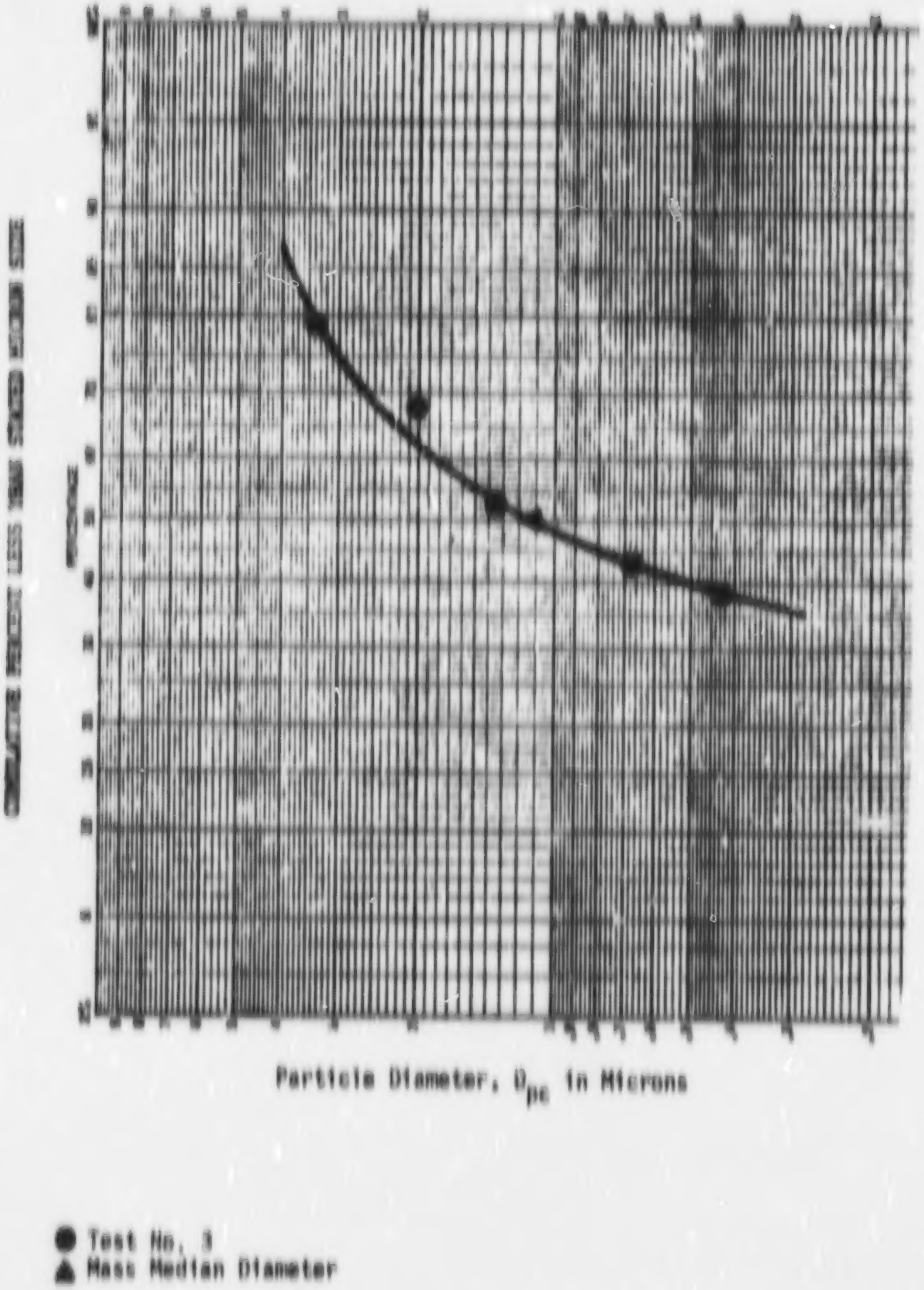
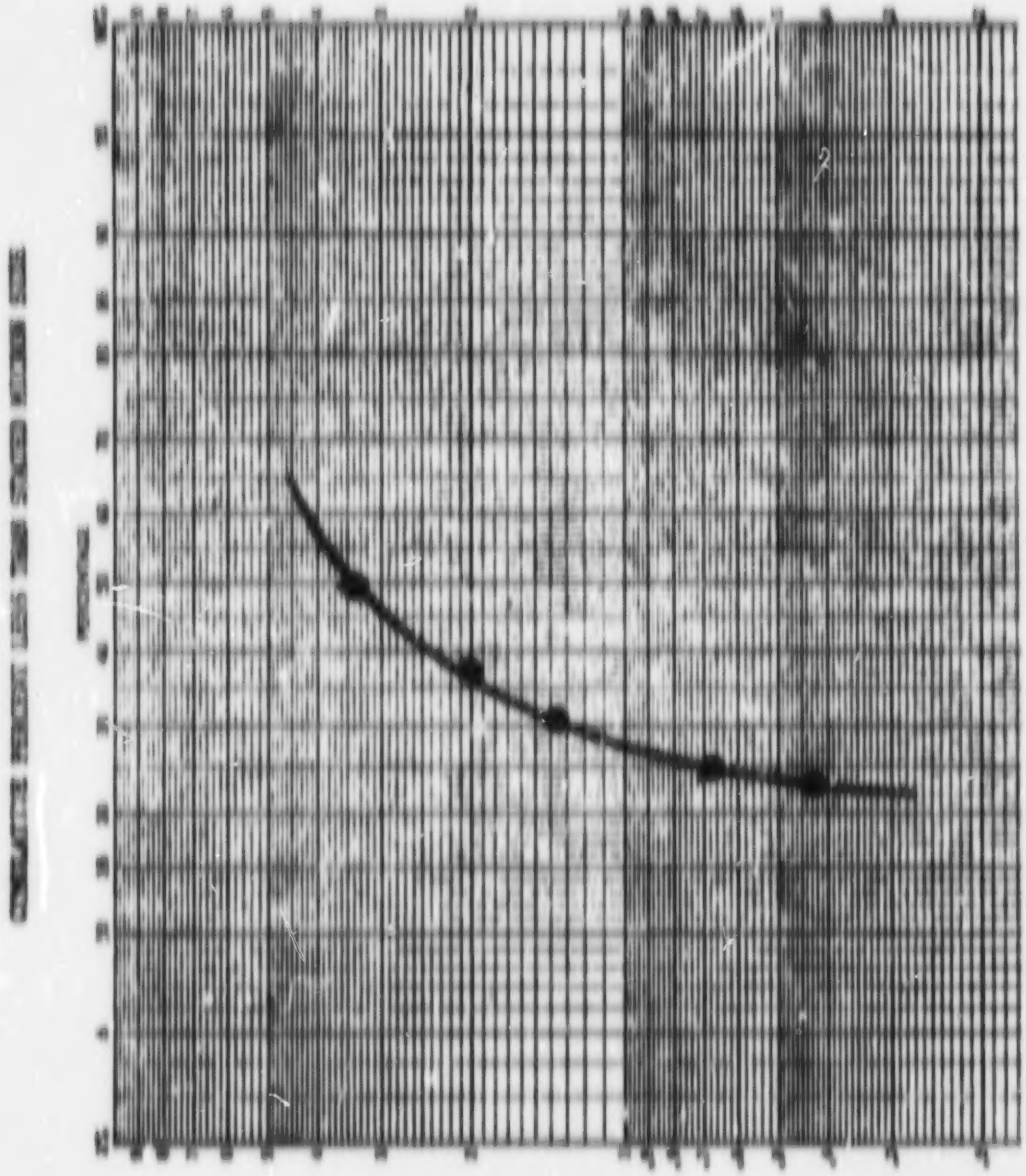


FIGURE B-4
PARTICLE DIAMETER vs. CUMULATIVE PERCENT
LESS THAN STATED SIZE



Particle Diameter, D_{pc} in Microns

● Test No. 6
▲ Mass Median Diameter

FIGURE B-5
PARTICLE DIAMETER vs. CUMULATIVE PERCENT LESS THAN STATED SIZE

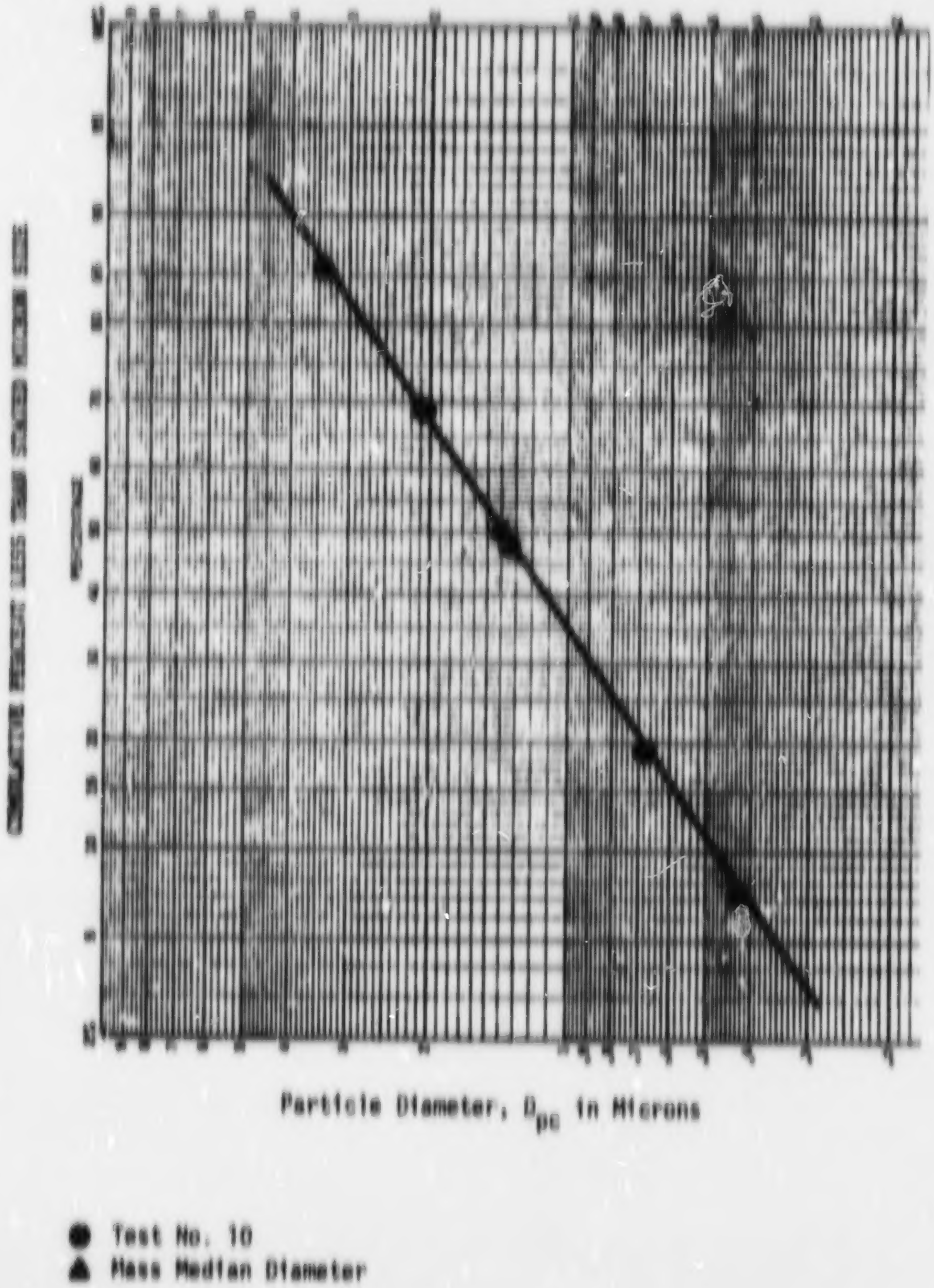
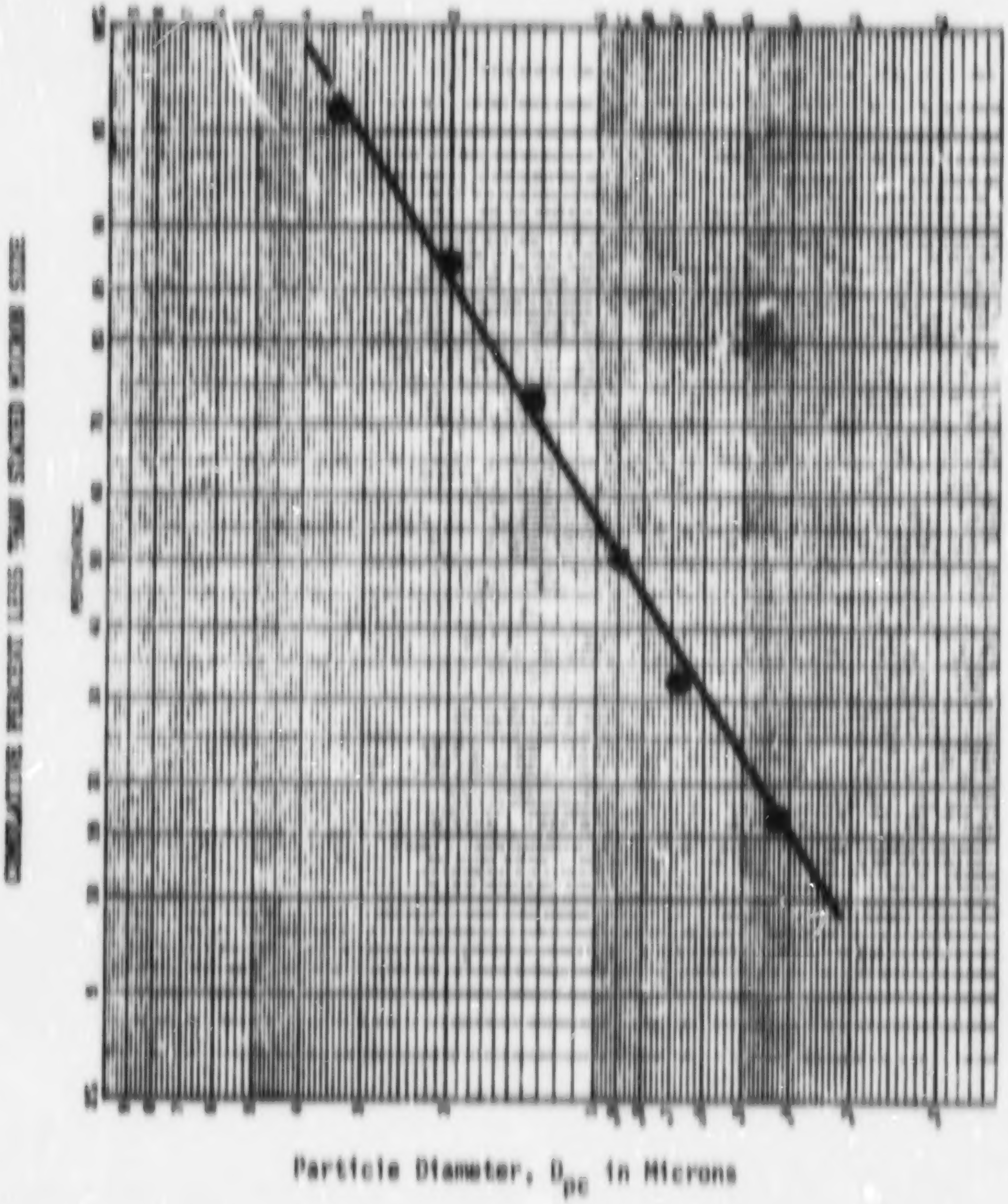


FIGURE B-6

PARTICLE DIAMETER vs. CUMULATIVE PERCENT
LESS THAN STATED SIZE



● Test No. 11
▲ Mass Median Diameter

FIGURE B-7
PARTICLE DIAMETER vs. CUMULATIVE PERCENT
LESS THAN STATED SIZE

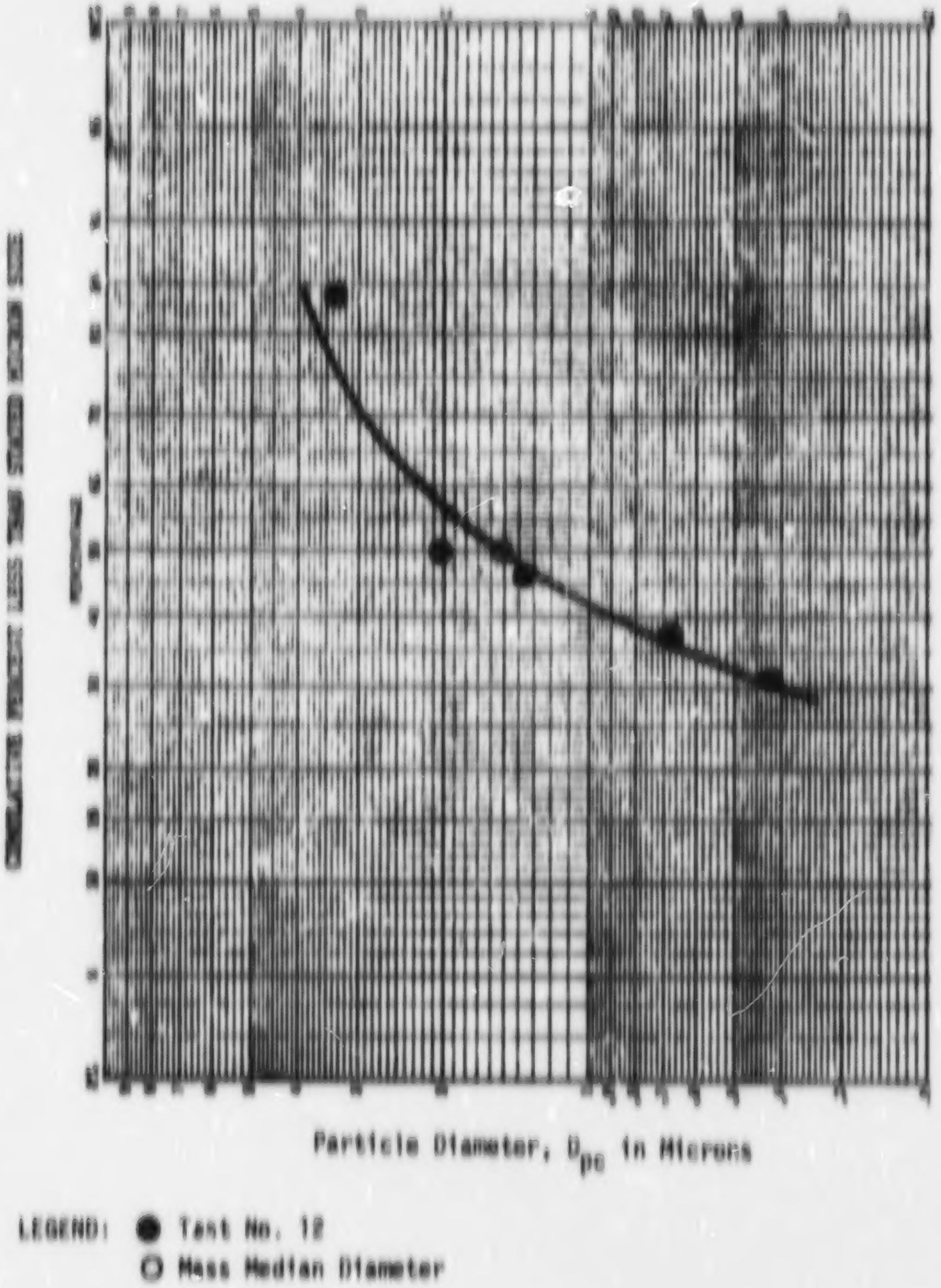


FIGURE B-8
PARTICLE DIAMETER vs. CUMULATIVE PERCENT
LESS THAN STATED SIZE

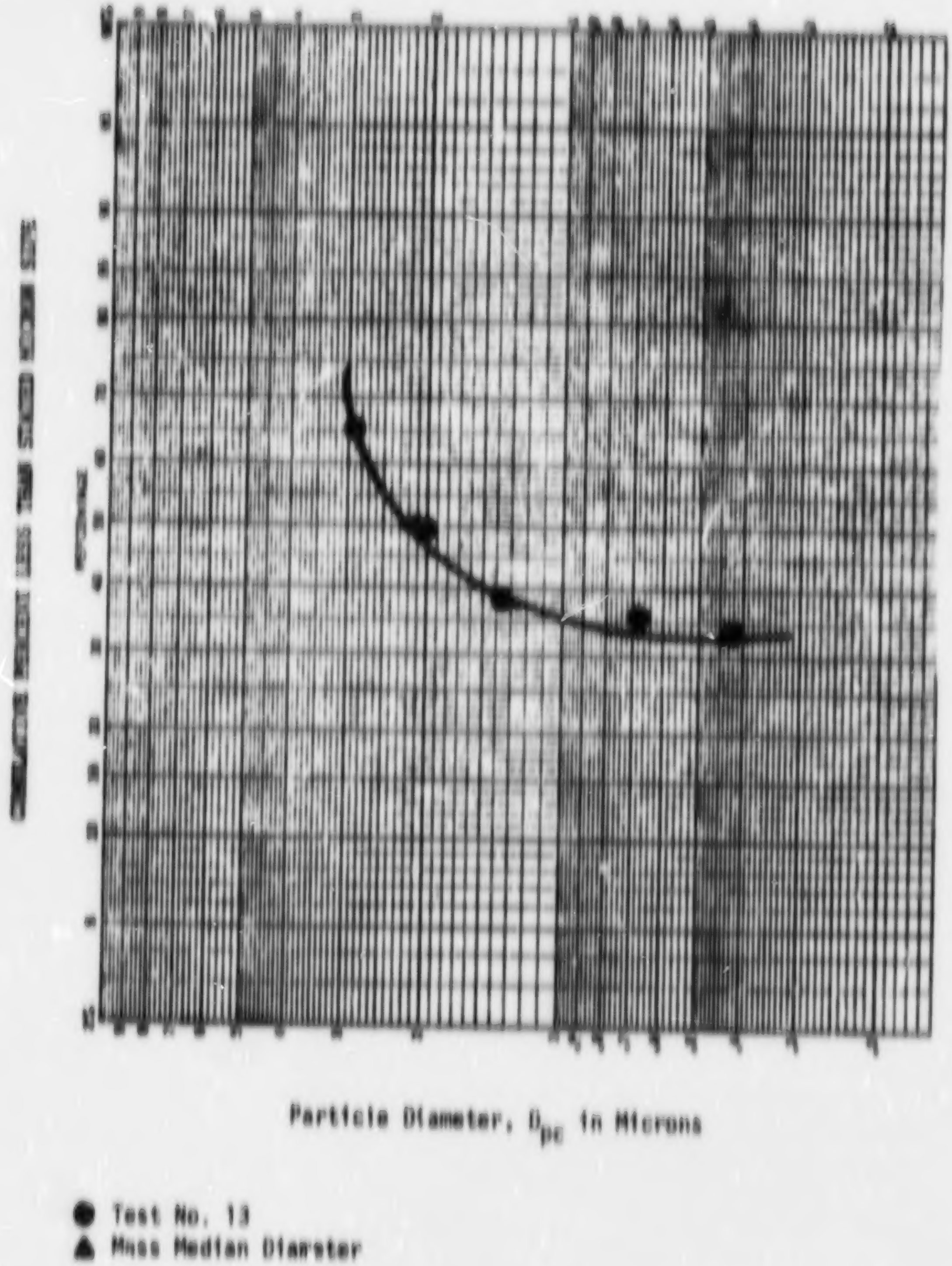


FIGURE B-9
PARTICLE DIAMETER vs. CUMULATIVE PERCENT LESS THAN STATED SIZE

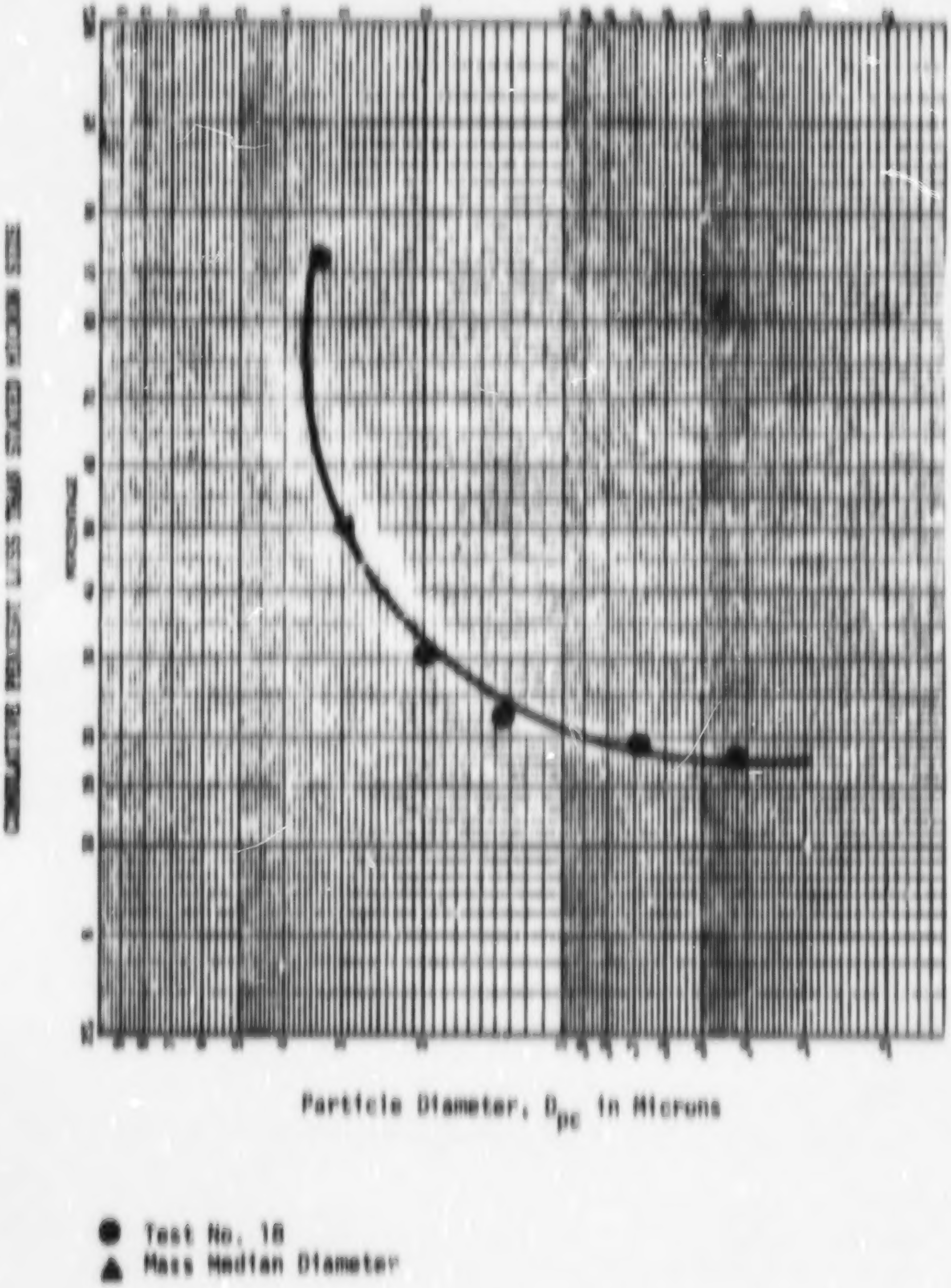


FIGURE B-10

PARTICLE DIAMETER vs. CUMULATIVE PERCENT
LESS THAN STATED SIZE

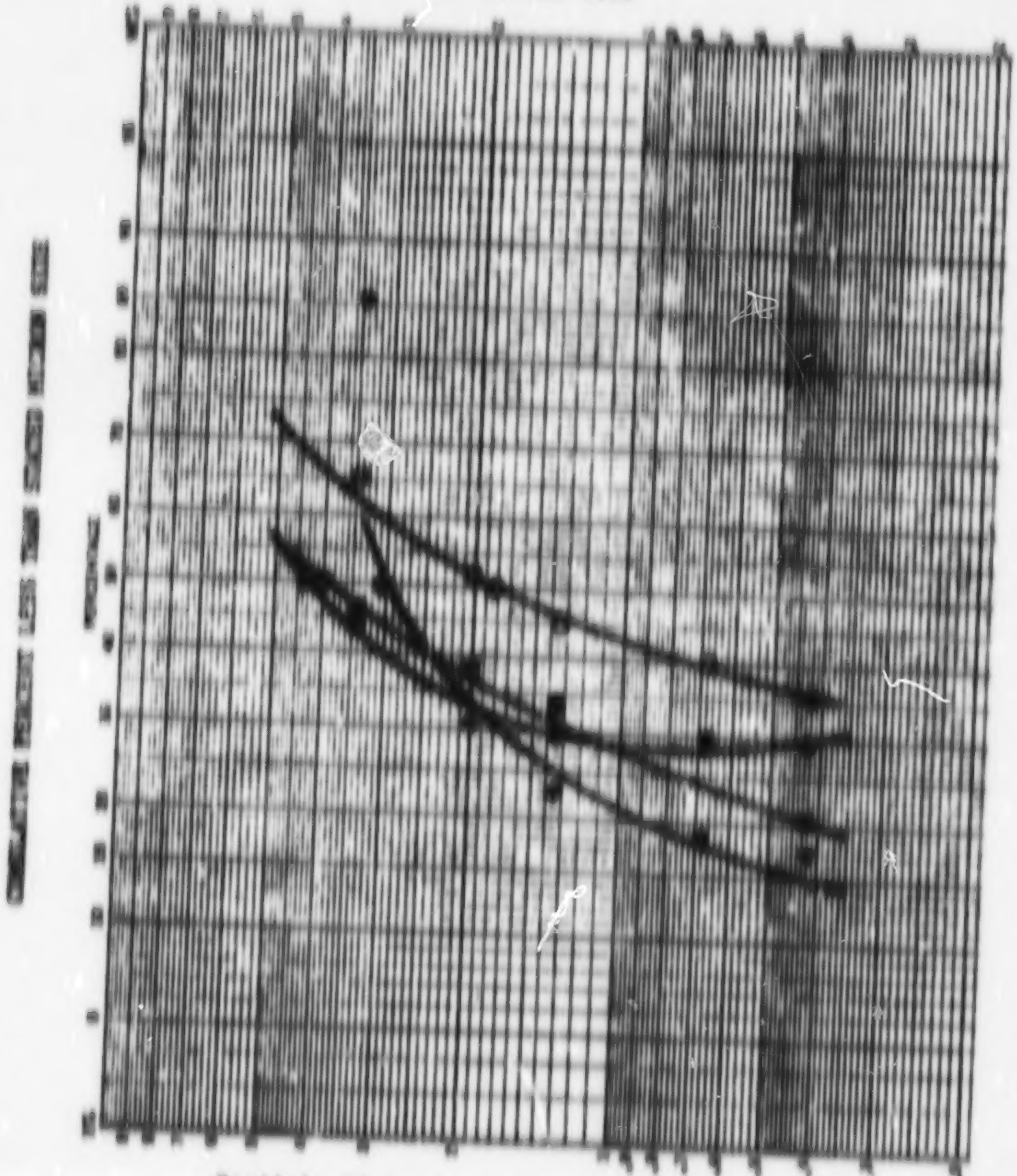


FIGURE B-11
PARTICLE DIAMETER vs. CUMULATIVE PERCENT
LESS THAN STATED SIZE

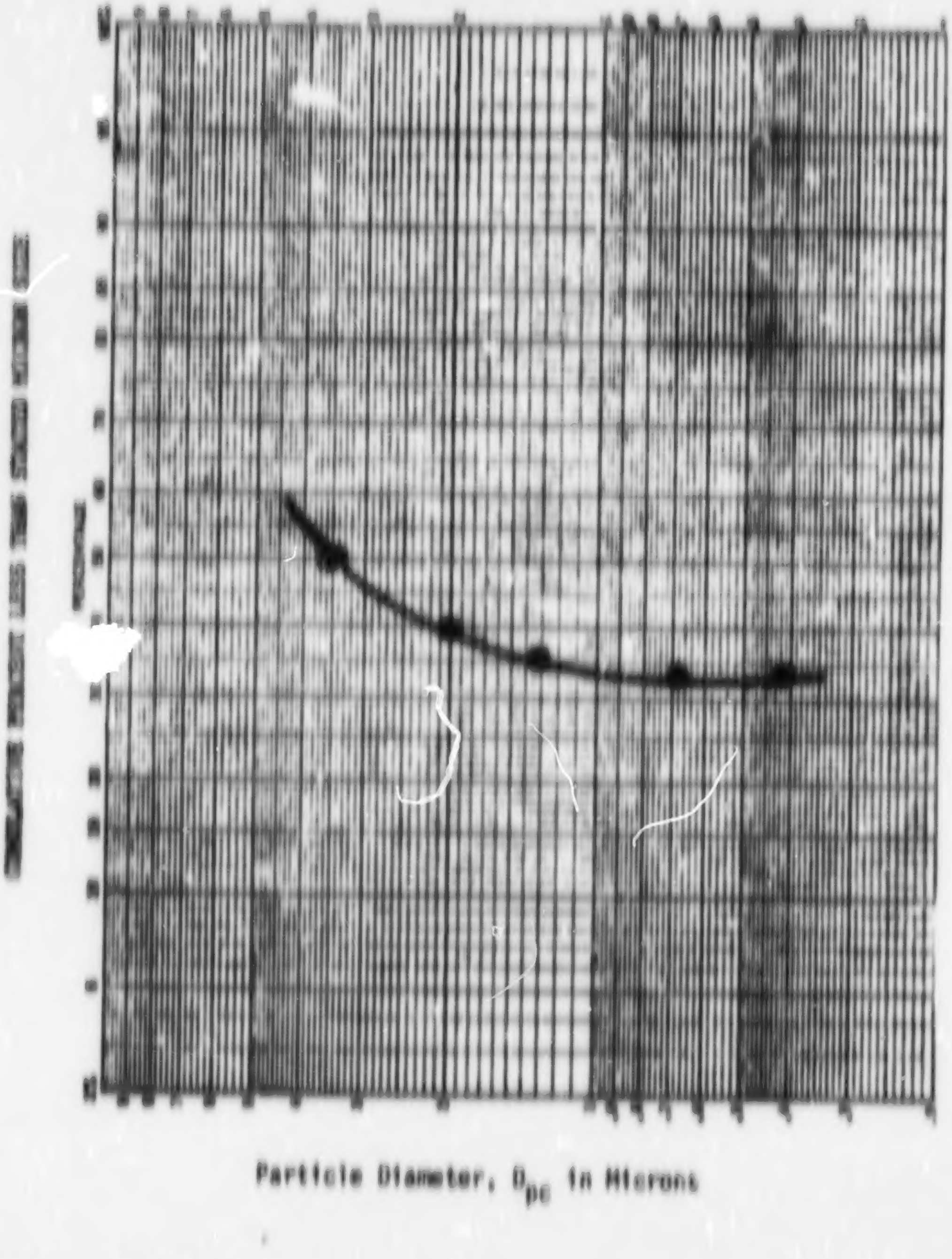
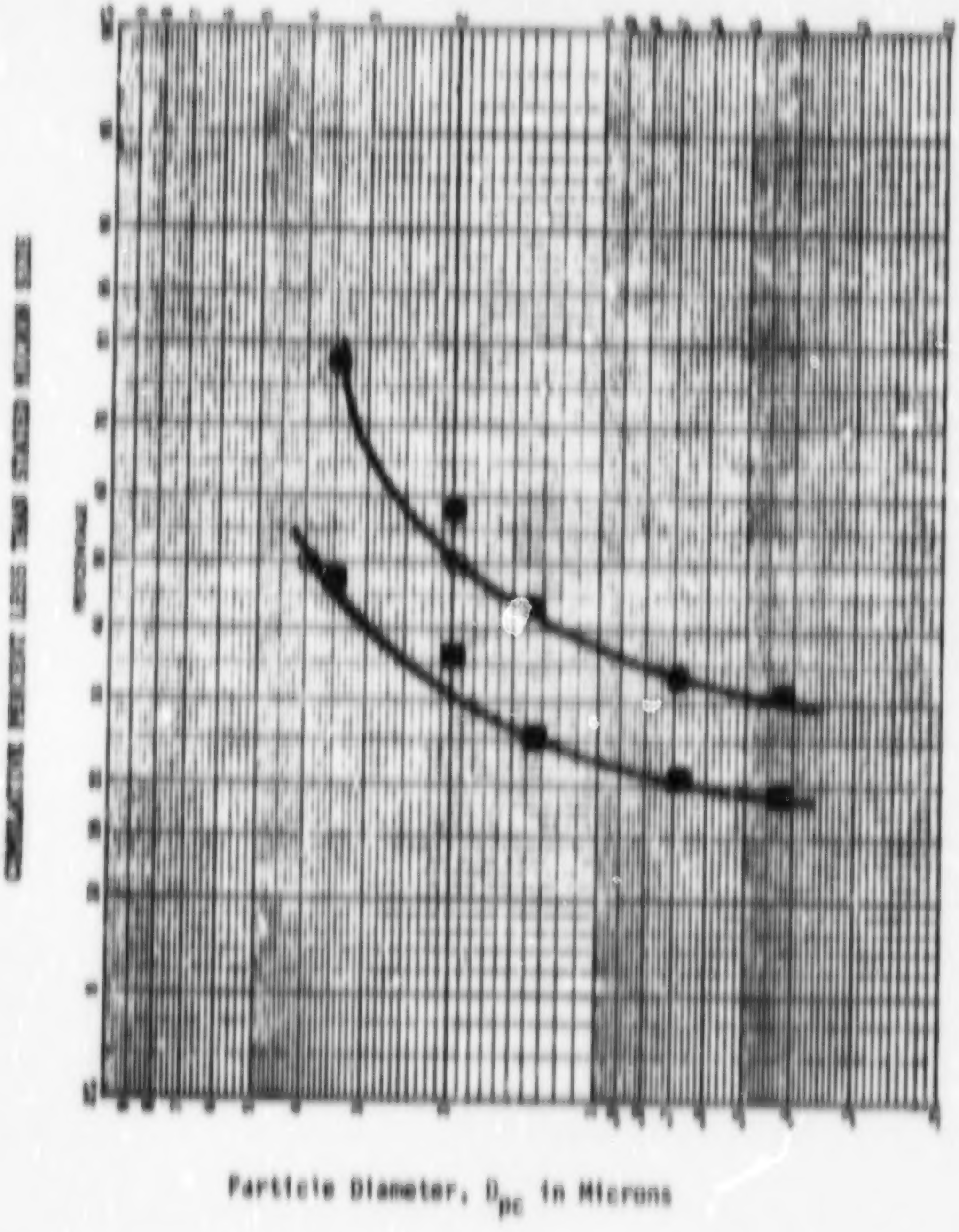


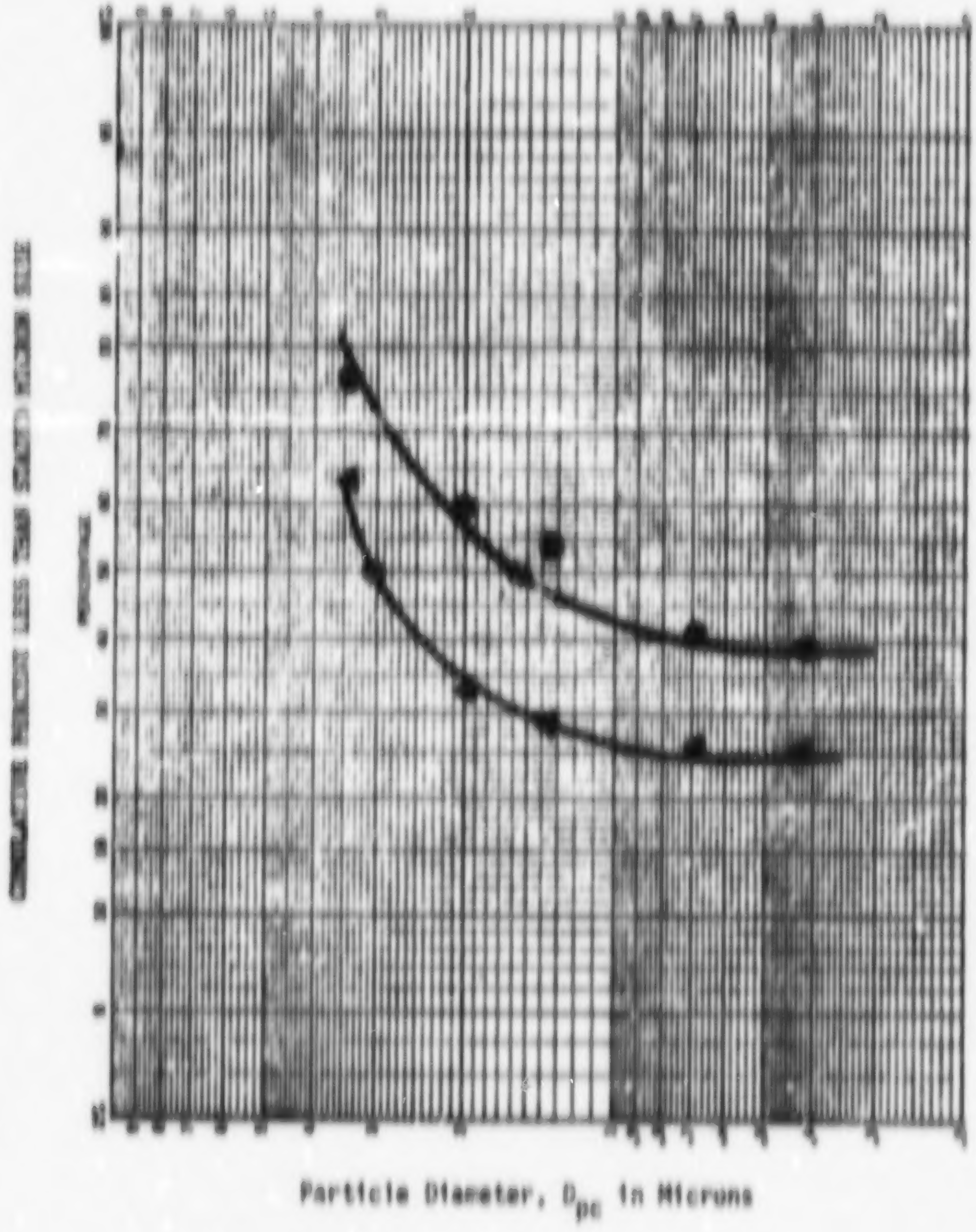
FIGURE B-12
PARTICLE DIAMETER vs. CUMULATIVE PERCENT LESS THAN STATED SIZE



Particle Diameter, D_{pc} in Microns

LEGEND:
● Test No. 29
■ Test No. 31
○ Mass Median Diameter

FIGURE B-13
PARTICLE DIAMETER vs. CUMULATIVE PERCENT LESS THAN STATED SIZE



LEGEND:
- ▲ Test No. 28
- ● Test No. 30
- ○ Mass Median Diameter

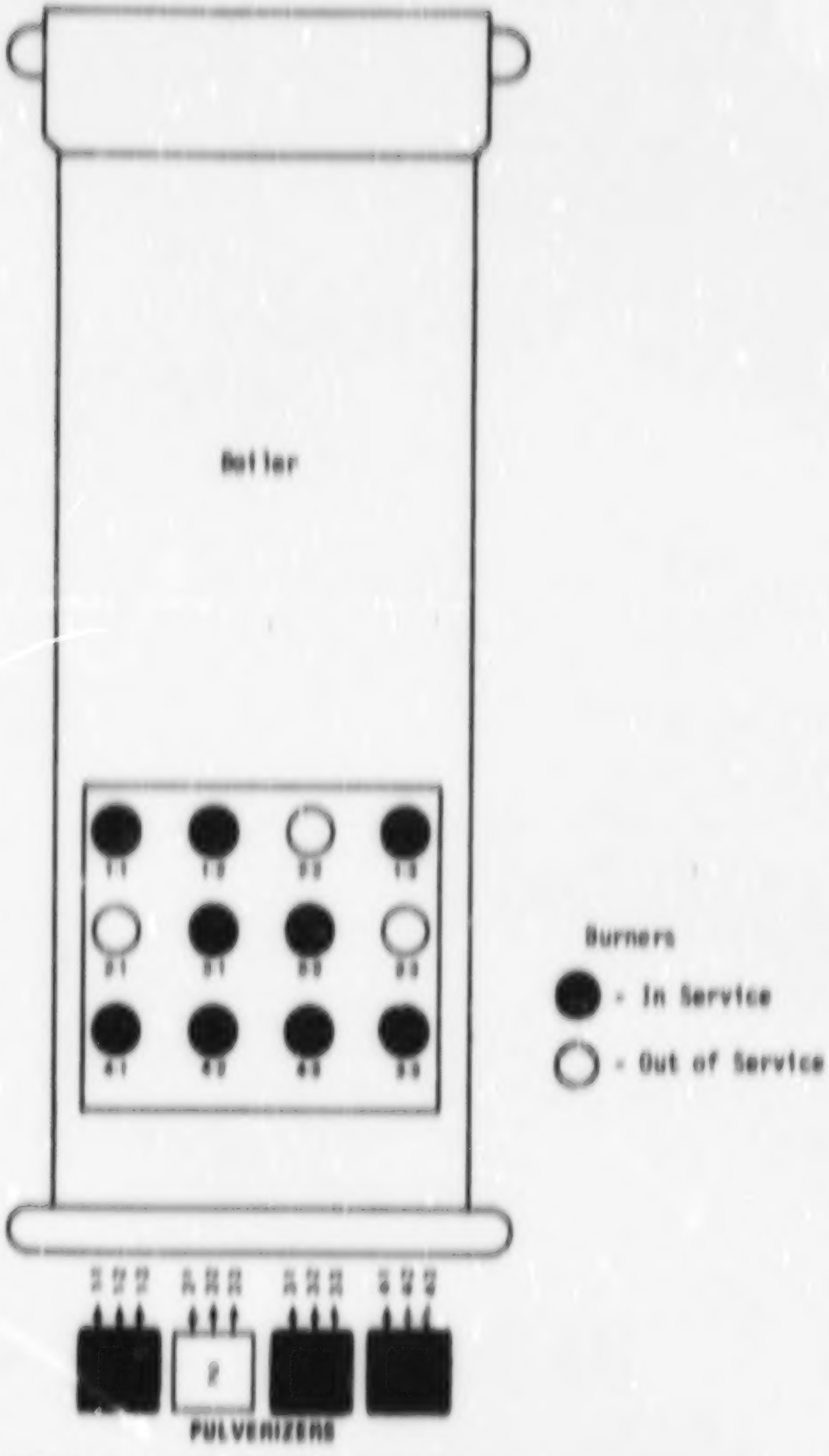

Boiler
Burners
● - In Service
○ - Out of Service
2
PULVERIZERS

FIGURE B14 FUEL DISTRIBUTION TO BURNERS

Test No. 31

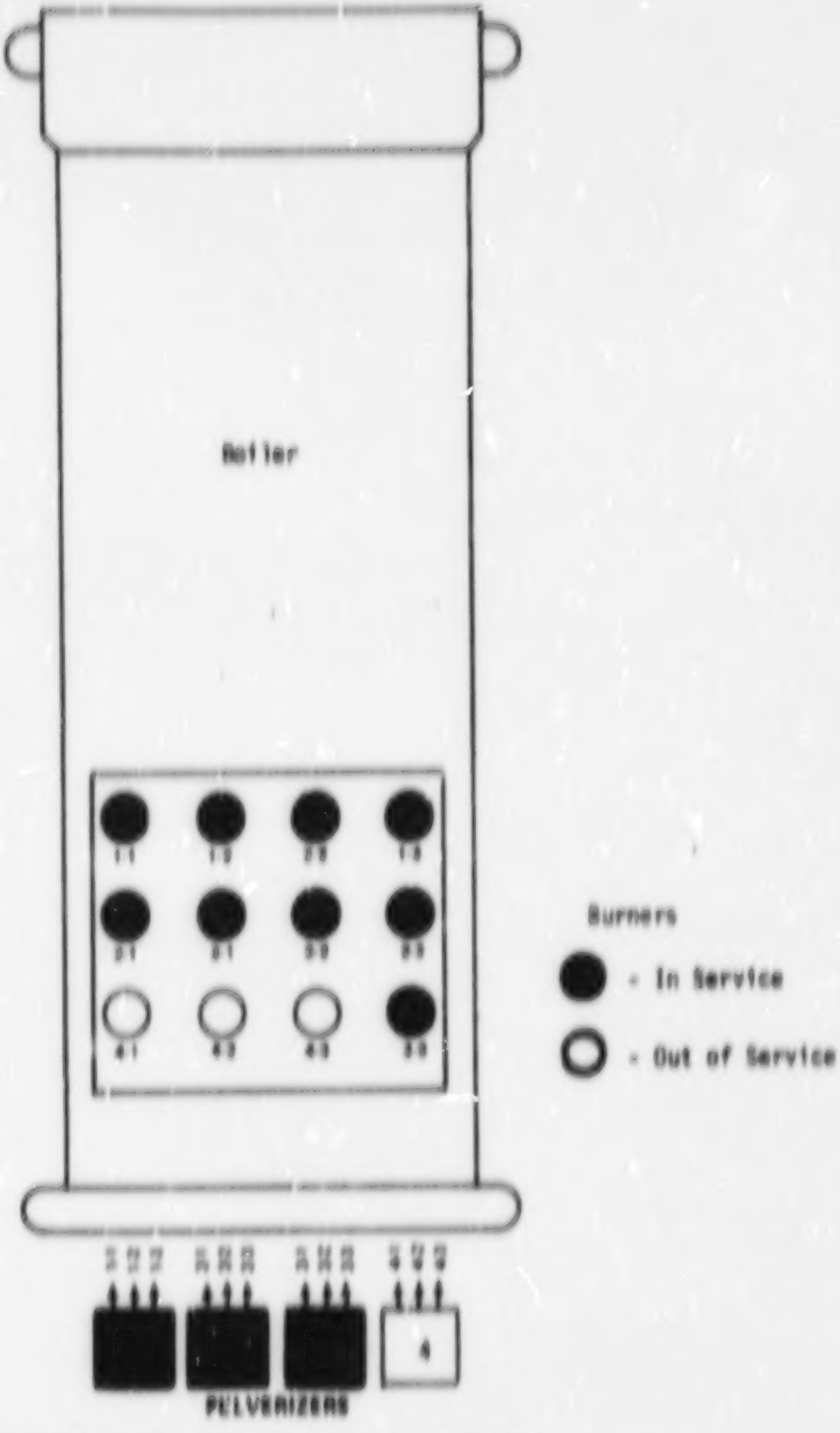

Boiler
11
12
22
13
21
31
32
23
41
42
43
33
Burners
● - In Service
○ - Out of Service
4
PULVERIZERS

FIGURE B15 FUEL DISTRIBUTION TO BURNERS

Test No. 28, 32, 34

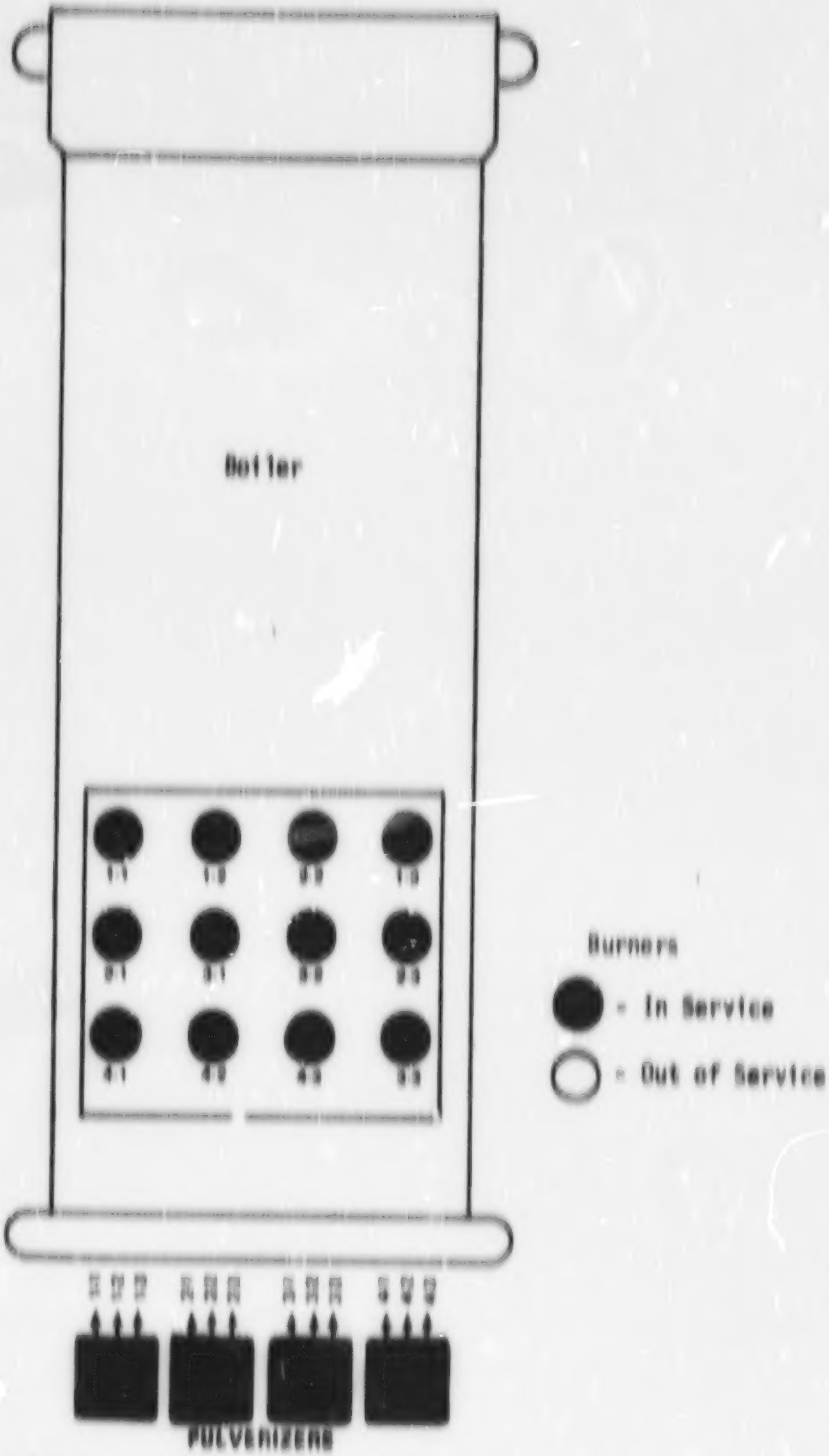

Boiler
11
12
22
13
21
31
32
23
41
42
43
33
Burners
● - In Service
○ - Out of Service
PULVERIZERS

FIGURE B16 FUEL DISTRIBUTION TO BURNERS

Test No. 24, 25, 29, 30, 33, 35

APPENDIX C. TEST METHODS

C.1 SAMPLING

C.1.1 Coal and Refuse

Coal was sampled by the NIPSCO coal handler from the coal hoppers to make composites of raw coal, using sampling probes designed by NIPSCO. Apparatus and procedure of ASTM-D-2234.72 governed sampling. The composite after test completion resided in a milk pail. Its size was reduced by riffling. A one quart mason jar sample was submitted for ultimate and proximate analysis. Another portion was retained. A test series composite sample was then created for all 1% S coal tests, etc. The coal handler was told when to begin, and since tests lasted up to 3.3 hours he continued to sample until instructed to stop.

Pulverized coal was sampled from feed pipes to make composites of as fired coal using the apparatus and procedure of ASME PTC-4.2.

Raw ("as received") coal scale tripper integrator readings were obtained at the station instrument panel at 30 min. intervals. Each calibrated trip was 100 lbs. The data was inspected for drift of fuel firing rate.

Fly ash samples were taken from the bottom of ESP ash hoppers at the mid point of each test. Ash from 3 fields (hoppers A-2, B-2 and C-2) was composited before analysis. Access was by ladder. Hoppers were run empty at the start of each test so that material collected represented current conditions. Samples were analyzed by CTE for loss on ignition ("percent dry ash") and sulfur content. Also selected samples were analyzed by TRW for halogens.

TRW provided NIPSCO with detailed written instructions for coal and refuse sampling.

C.1.2 Flue Gas

Sampling and analysis procedures, except where otherwise specified, were in accordance with standard methods as published in the Federal Register, Volume 36, Number 247, Part II, December 23, 1971, see Table C-1. The various test

TABLE C-1

FLUE GAS SAMPLING METHODS

Parameter	Method* - Collection
Particulate - outlet	EPA Method 5 and ASME
Particle size	Brink Cascade Impactor
Trace Metals	EPA Method 5
Sulfur oxides	SO_2-EPA Method 6, SO_3- Modified Shell Development Method
Nitrogen oxides	EPA Method 7
Hydrocarbons	EPA Method 3
Mercury	"Sampling and Analysis of Mercury Vapor in Industrial Streams Containing Sulfur Dioxide" Statnick, et al.
Halogens	Midget bubbler train, 0.01 N NaOH absorbing solution
Hydrogen sulfide	EPA Method 11 with hydrogen peroxide pre-scrubber.
Stationary gases	EPA Method 3
Moisture	EPA Method 5
Particulate - inlet & outlet	ASME

*EPA Methods are found in Reference (5)

The ASME Method is found in Reference (6) parameters evaluated by the referenced method or other stated methods were as follows:

C.1.2.1 Particulates

Two test methods were employed in the particulate testing program.

Due to the expected high particulate grain loading present at the precipitator inlet, ASME methods were utilized to conduct the efficiency testing of the precipitator. The ASME method utilized an in-situ alundum thimble as the filtering medium. The thimble was dried and weighed prior to the sampling and again following the sampling to determine total mass of particulate matter collected. The grain loading of the particulates in the inlet and outlet flue gas was then determined from the data collected during the isokinetic sampling.

The precipitator outlet location was also tested for total particulates using Methods 1, 2, and 5, Federal Register, December 23, 1971, and Method 6, Federal Register, August 17, 1971. The particulate matter collected with this method was also analyzed for trace metals which is discussed in one of the following descriptions.

The EPA particulate sampling train was modified as shown in Figure C-1. The filter box was redesigned to allow for a flexible tube connection between filter and impingers so that the impinger bath could remain stationary while having the filter box coupled rigidly to and moving with the probe.

C.1.2.2 Particle Size

Size distribution of the particulate matter was determined at the precipitator outlet location by an in-situ Brinks cascade impactor. The cascade impactor separated particles into six (6) different size categories, varying from greater than seven (7) microns in diameter to less than one-tenth (.1) micron.

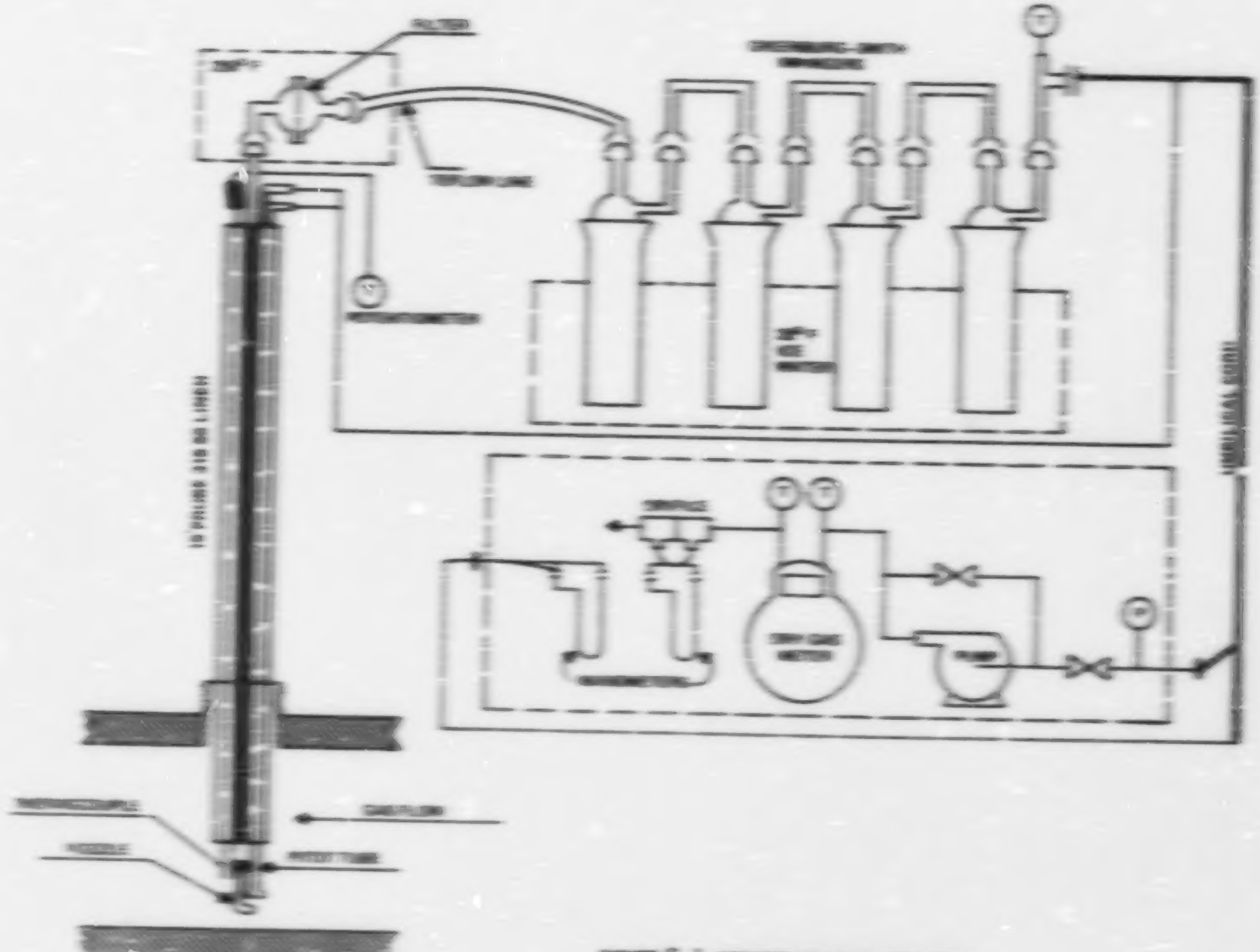


FIGURE C-1 [illegible]

C.1.2.3 Nitrogen Oxides

Method 7, Federal Register, December 23, 1971. A grab sample was collected in an evacuated flask containing a dilute solution of sulfuric acid and hydrogen peroxide as an absorber. The nitrogen oxides, excepting nitrous oxide, were measured colorimetrically using the phenoldisulfonic acid procedure (PDS). The nitrogen oxides sampling was conducted at the precipitator outlet location.

C.1.2.4 Sulfur Oxides

The precipitator outlet location was sampled for sulfur dioxide and sulfur trioxide.

The sulfur dioxide analysis was conducted in accordance with Method 6, Federal Register, December 23, 1971. SO_2 was collected in a 3 percent aqueous hydrogen perioxide solution and measured by the barium perchlorate titration method.

The sulfur trioxide concentrations were determined using the Modified Shell Development Method. SO_3 was collected in an absorbing solution containing 80 percent isopropanol. The sulfate formed in the absorber was titrated with a standard barium perchlorate titrant using thorin as an end point indicator.

C.1.2.5 Stationary Gases

Method 3, Federal Register, December 23, 1971 was the method employed for this analysis. In lieu of an Orsat analyzer, a portable gas chromatograph (AID) with a thermal conductivity detector was utilized. Using the GC-TC enabled test personnel to complete a more precise analysis and also yields a permanent record of the data acquired. The stationary gas analysis and sampling was conducted at both the inlet and outlet precipitator test locations. Orsat analysis equipment was used to spot check the GC-TC results.

C.1.2.6 Moisture Determination

Method 4, Federal Register, December 23, 1971. The percent of moisture in the stack gases was determined at both locations on a volume basis.

C.1.2.7 Hydrogen Sulfide

Method 11, Federal Register, June 11, 1973 was the procedure followed in the H_2S analysis at the precipitator outlet.

The H_2S was collected in an alkaline cadmium chloride solution with a peroxide pre-scrubber to remove SO_2, which interferes with the absorbing solution. The amount of cadmium sulfide precipitate was determined iodometrically.

C.1.2.8 Hydrocarbons

The outlet test location was sampled for total hydrocarbons. A bag sample was extracted from the flue gas and was analyzed on a Flame Ionization Detector (FID), and compared against a known gas.

C.1.2.9 Halogens

Fluorides and chlorides were sampled by a continuous method using 0.01N NaOH in a midget impinger absorption train. For total fluorides, or total chloride determination, the sample probe and inlet tubing were included in the washings taken for analysis.

C.1.3 Flow Measurement

Gas flow determinations were made using type "S" pitot tubes and thermocouple actuated potentiometers in accordance with EPA Methods 1 and 2.

C.2 DATA COLLECTION

C.2.1 General

Mitchell Station instrument data from the station control room were recorded at intervals of 30 minutes during each test run. Several items were not actually located in the control room and include: barometer, precipitator controls and F.D. fan air temperature and humidity.

The completed test data was examined for averages and trends before keypunching.

C.2.2 Steam Generator Operating Data

The steam generator operating data recorded for the Baseline Test included all major gaugeboard readings, coal scale readings, atmospheric pressure and dry bulb temperature - relative humidity of the air at the inlet to the forced-draft fan as recorded manually on the operating conditions log sheet. These data were recorded at about hourly intervals throughout the duration of each test. Averages for each parameter were noted, as well as trends if variations were encountered. Data were transcribed to punch cards. Fuel consumption rates were calculated from integrator readings on each coal feeder. Each integrator trip represented 100 lbs. Rates on each scale were added to yield the total. Readings were twice hourly.

C.3 ANALYTICAL METHODS

C.3.1 Coal Proximate and Ultimate

ASTM Standard Method D271.

C.3.2 Coal Screen Size

ASTM Standard Method D197.

C.3.3 Fly Ash Loss on Ignition

ASTM Standard Method D271. Dry basis only, % ash is reported.

C.3.4 Fly Ash Sulfur

ASTM Standard Method D1757.

C.3.5 Primary Flue Gas Parameters

Analytical methods for particulates, nitrogen oxides, sulfur oxides, stationary gases, hydrogen sulfide, and hydrocarbons are included by reference in Subsection C.1.2 and Table C-1.

C.3.6 Fluorides

Fluoride gas and mist after absorption in a sodium hydroxide solution is determined by specific fluoride ion electrode. Fluoride dust is fused with sodium hydroxide and determined colorimetrically in a Technicon Auto Analyzer using H_2SO_4 distillation and lanthanum - alizarin complexone reagent.(12)(13)

C.3.7 Chlorides

Chlorine in coal is part of the "ultimate" at no extra charge and is done by the Mohr Method (ASTM D2361) using low-chlorine Eschka digestion.

CTE has agreed to report the chlorine percentage to three decimal places (i.e. 0.041 rather than 0.04).

Chlorine analysis in flue gas is accomplished by chloride specific ion electrode in accordance with the Instruction Manual for Chloride Analysis, Orion Research, Inc., Cambridge, Mass. As little as .02 ppm aqueous Cl^- can be detected by this method.

C.3.8 Trace Metals

Trace element distributions have not yet been determined for more than a few coals. Consequently there are no commonly accepted or trace element analysis procedures established that can be used in this program. The situation is much the same in the case of trace element analyses of flue gas particulate from coal combustion sources. There is at present a great deal of effort being directed at establishing standard procedures on the part of ASTM and EPA, but their recommendations will not be available for some time. The trace element analysis methods recommended therefore for use in this work are those used or developed by TRW under Contract 68-02-0647 (Survey of Meyer's Process Potential for Chemical Desulfurization of United States Coals). The adequacy of these procedures in providing both accurate and precise trace element levels at least for coal samples, was demonstrated under this contract by analyzing standard coal samples supplied by the Illinois Geological Survey and the National Bureau of Standards.

The proposed analytical procedures for determining trace element levels in NIPSCO coal, fly ash and flue gas samples are described below.

Be, Ca, Cd, Cr, Cu, Li, Mg, Mn, Ni, Pb, Sn, Sb, V, Zn

Analyses of these elements in coal and flue gas will be performed by atomic absorption methods using one coal ash or flue gas sample. In the analysis of the coal sample, the sample will be ashed using a low temperature oxygen plasma asher (International Plasma Corporation, Model 1001B). Upon complete ashing of the coal sample, the ash will be taken into solution by a

HNO_3-HF acid mixture, diluted to a convenient volume and stored in polyethylene containers until used. Teflon or Nalgene labware will be used for HNO_3-HF ash dissolution to prevent possible contamination or loss of sample trace elements. For flue gas particulate samples collected on glass fiber impactors, a small representative portion of the pads will be treated with a HNO_3-HF acid mixture to solubilize the sample. The resulting solution will be diluted and handled in an identical fashion to the HNO_3-HF acid solubilized coal ash samples.

Solutions prepared in the above fashion will be analyzed directly for 12 elements using a Fisher Scientific Co. Model 810 atomic absorption spectrophotometer employing operating conditions listed in Table C-2. Since the Model 810 is a dual channel instrument automatic background correction can be incorporated into the measurement to enhance the accuracy of the determination. The wavelengths used for background correction for each of the elements as well as the analytical wavelength are also listed in Table C-2.

Selenium

Analyses of Se in coal samples may have to be performed using a flameless atomic absorption procedure if the flame atomization method described above is too insensitive for this study. In this event, Se analyses will be performed using a portion of the solution from the coal ash sample and a Fisher Scientific Company Model micro thermal analyzer attachment for the AA spectrophotometer. For all of the analyses using the micro thermal analyzer background corrections will be applied and standard additions of the element will be used for quantitation purposes.

Mercury

The analysis procedure for Hg in coal is one currently in use by the U. S. Bureau of Mines. In this procedure the coal sample is combusted in a Leco Instrument Co. tube furnace equipped with an O_2 flow. The combustion gases are swept through an unheated quartz tube packed with gold foil for amalgamating the Hg vapor. After initial combustion is complete, the gold

TABLE C-2

ATOMIC ABSORPTION ANALYTICAL PARAMETERS

A) Flame Methods

Element	Analytical (Å)	Slit (Å)	Background (Å)	Slit (Å)	Flame Conditions
Mn	2795	4	2802	4	Air-Acetylene
Cu	3247	10	3171	10	Air-Acetylene
Cr	3579	4	3563	4	N_2O-Acetylene
Ni	2320	2	2316	2	N_2O-Acetylene
Sn	2246	4	2186	4	Hydrogen-Air
Ag	3281	10	3257	10	Air-Acetylene-Lean
Sb	2176	4	2161	4	Air-Acetylene-Lean
V	4408	2	——	—	N_2O Acetylene- Emission Mode
Pb	2833	10	2850	10	Air-Acetylene-Lean
Cd	2288	4	2297	4	Air-Acetylene-Lean
Zn	2139	10	2097	10	Air-Acetylene-Lean
Li	6708	10	6696	10	Air-Acetylene-Lean
Be	2349	10	2312	10	N_2O-Acetylene

TABLE C-2 (CONTINUED)

ATOMIC ABSORPTION ANALYTICAL PARAMETERS

B) Flameless AA Methods

Element	Analytical (A)	Slit (A)	Background (A)	Slit (A)	Flame Conditions
Hg	2537	10	———	—	Ar Flow, 2 SCFH, use 10cm Cell Heated To 200°C
Sb	2176	10	2261	10	Dry at Instrument Setting of 50 for 2 Min. Atomize at Setting of 80 for 1 Sec. at Ar Flow of 14 SCFH
Se	1962	10	1979	10	Same Settings as for Sb, Except for Addition of H_2 whose Flow is Regulated at 10 psig
Sn	2863	4	2880	4	Same Setting as for Sb

foil trap is fitted with an Ar purge and heated. The Hg vapor released from the foil is swept into a quartz flow cell positioned in the AA and Hg is determined using conditions in Table C-2. Calibration is accomplished using known volumes of Hg saturated air in the analysis procedure.

Hg in flue gas is determined as follows: The solutions will be placed in a closed reaction vessel and a reducing agent added to liberate Hg vapor. The Hg vapor will then be flushed from the reaction vessel into an AA cell (flameless method).

Arsenic

The analytical procedure to be used for As in coal is a modified(14) U. S. Bureau of Mines colorimetric method. In this procedure a coal sample is fused and the residue dissolved in a mineral acid solution. From this solution arsine is evolved through oxidation of metal zinc and the zinc concentration produced measured as the colored dithiocarbonate complex using the DK2A spectrophotometer. A similar procedure without MgO fusion will be used for the analysis of As in the flue gas samples.

The analysis procedures outlined above are expected to be used for the Baseline Test Program. However, as standard or more accurate and cost effective procedure become available, it is expected that they will be substituted as appropriate.

APPENDIX D. FIELD TEST LOGS

FIELD TEST LOG

8 May 1974 - 23 May 1974

8 May : Equipment truck and lab trailer departed McLean.

9 May : Equipment truck and lab trailer arrived Mitchell station. Began deployment of equipment. Intermittent heavy rain.

10 May : Continued deployment of equipment. Mitchell No. 11 forced down
11 May : by fire in Mill 2, due to loss of coal flow due to wet coal and/
or tramp iron. Scheduled down in p.m. for air heater cleaning.

12 May : Hangers on cold reheat line snapped while unit was coming on. Down to repair.

13 May : Test crew assemblud. Completed deployment of equipment.

14 May : Unit on at about 50MW with Mill 2 and Mill 3 down, Mill 3 with broken retainer rings. Ran velocity traverses at outlet with Unit No. 6 at 120MW. No negative flows.

15 May : Both mills still down. Began 46-3-WO test at 1130.

16 May : No. 2 mill back. 92MW available. One test aborted, rain. Second test cancelled, rain.

17 May : Completed 92-3-WO and 92-3-WI tests with three mills, light rain.

18 May : No tests, rain.

19 May : Completed 92-3-WO and 92-3-WI tests with three mills.

20 May : Completed 92-3-WO and 92-3-WI tests with three mills. All 92MW tests completed.

21 May : Mill 3 not available to start 115MW tests in morning. Afternoon, rain.

22 May : 115MW not available until 1040, FD fan damper. Delayed start until 1400 due to rain. Completed two (115-3-WO) tests.

23 May : Completed 115-3-WO and 115-3-ASH tests.

24 May : Completed two (115-3-ASH) tests.

25 May : Completed two (110-3-XSA) tests. Bearing and vibration problem on west I.D. fan. Limited control of F.D. fan dampers, resulting in air limitation. Performed tests at 110MW to obtain additional excess air.

26 May : Completed two (46-3-WO) tests with three mills.

27 May : Completed 110-3-XSA test. Opened access door on each air heater by one 2x4 width. Completed 115-3-VOL test.

28 May : Completed two (115-3-VOL) tests with access doors full open.

29 May : West I.D. fan shutdown at 0600, bearing high temperatures. Unable to complete three (115-3-MISC) tests. Further testing cancelled until next scheduled field tests.

FIELD TEST LOG

13 April 1975 - 2 May 1976

13 April : Equipment truck and lab trailer departed Vienna.

14 April : Equipment truck and lab trailer arrived Gary. NIPSCO began calibration of coal scales.

15 April : Began deployment of equipment. Calibration of coal scales completed.

16 April : Deployment of equipment completed.

17 April : Completed one 115-3-WO Misc test. Boiler was load limited to about 112 MW due to feed water limitation.

18 April : Completed one 115-3-WO Misc test. Delays due to gentle rain throughout day prevented completion of more than one test. During the night, NIPSCO lost all coal feed to station due to a coal slide into the reclaiming hopper. The third 115-3-WO Misc test was cancelled. Low sulfur coal for testing did not start to No. 11 bunker until late on 23 April.

24 April : Filling No. 11 bunker with test low sulfur coal.

25 April : Completed two 115-1-WO tests.

26 April : Completed two 46-1-WO tests. Coal mills 3 and 4 were down. Boiler feed pump 11W was down. FD fan 11W was down. Gas recirculating damper was about 20% open to control temperatures.

27 April : Tests postponed, rain.

28 April : Completed one 92-1-WO and one 92-1-WI test. No. 4 mill was down during 92-1-WO test. Short outages of mills occurred due to feed hopper pluggage due to wet coal.

29 April : Completed one 92-1-WO and one 92-1-WI test. Continued to have feed hopper pluggages, resulting in a load limitation to 80MW for 35 minutes during 92-1-WO test.

30 April : Completed one 92-1-WO test. No test during afternoon hours, rain.

1 May : Completed one 115-1-WO test and one 92-1-WI test. No. 4 mill down during 92-1-WI test.

2 May : Completed one 115-1-WD test to backup first test of this test set during which the boiler may not have been stabilized on low sulfur test coal. Equipment disassembled and packed for return to Vienna.

APPENDIX E. GLOSSARY OF TERMS

GLOSSARY OF TERMS

ACF	Actual cubic feet
acfm	Actual cubic feet per minute
AF	As fired
AH	Air heater
APH	Air preheater (same as air heater)
ASME	American Society of Mechanical Engineers
BFP	Boiler feed pump
BTU	British thermal unit
CE	Concentration effect
cfm	Cubic feet per minute
circ	Circulation
demo	Demonstration
eff	Efficiency
EPA	Environmental Protection Agency
ESP	Electrostatic precipitator
FD	Forced draft
FGV	Flue gas volume
FID	Flame ionization detector
GC	Gas chromatograph
gl	Gross load
gr	Grain
HC	Hydrocarbon
HHV	High heating value
HLE	Heat loss efficiency
HVC	High volatile coal
ID	Induced draft
I/O	Input-output efficiency

GLOSSARY OF TERMS (Continued)

KWH	Kilowatt hours
M	Thousands
ma	Milliamps
macfm	One thousand actual cubic feet per minute
MMBTU	Million Btu's
MMLB/HR	Million pounds per hour
MSA	Mine Safety Appliance Company
MW	Megawatts
NDIR	Non-dispersive infrared
NIPSCO	Northern Indiana Public Service Company
NOx	Nitrogen oxides
ppm	Parts per million
ppmv	Parts per million by volume
ppmw	Parts per million by weight
psig	Pounds per square inch, gauge
PT	Pressure, temperature
PVT	Pressure, volume, temperature
SB	Sootblowing
scf	Standard cubic foot
scfm	Standard cubic foot per minute
SOx	Sulfur oxides
T&E	Test and Evaluation
Test Series One	Test series, boiler operating normally
Test Series Two	Test Series, boiler operating off-normal
Test Series Three	Tests 22 & 23, boiler operating normally
Test Series Four	Test series, high sulfur coal
Test Series Five	Test series, low sulfur coal
WL	Wellman Lord
XSA	Excess air